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16. ABSTRACT

The Tenth Annual Research Symposium on land disposal, remedial action, incineration and treatment of hazardous waste was held in Fort Mitchell, Kentucky April 3 through 5, 1984. The purpose of the Symposium was to present the latest significant research findings of ongoing and recently completed projects funded by the Solid and Hazardous Waste Research Division of the Municipal Environmental Research Laboratory and the Energy Pollution Control Division of the Industrial Environmental Research Laboratory to persons concerned with hazardous waste management.

These proceedings are for Session A, Hazardous Waste Land Disposal. Papers presented by Symposium speakers and poster presentation Abstracts in the areas of (1) Remedial Action (2) Pollutant Assessment and (3) Pollutant Control are compiled. Subjects discussed include landfill design and operation, waste leaching and analyses, pollutant migration and control, waste modification, surface impoundments, technology assessment, remedial action techniques and cost/economics.

This document covers Hazardous Waste Land Disposal only. A separate document concerned with Hazardous Waste Incineration and Treatment will be published by the Industrial Environmental Research Laboratory.

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Naomi P. Barkley
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

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These proceedings have been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimoney to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and the solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research--a vital communications link between the researcher and the user community.

These Proceedings present the results of completed and ongoing research projects concerning the land disposal of hazardous waste.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

PREFACE

These Proceedings are intended to disseminate up-to-date information on extramural research projects concerning land disposal, incineration, and treatment of hazardous waste. These projects are funded by the U.S. Environmental Protection Agency's Office of Research and Development and have been reviewed in accordance with the requirements of EPA's Peer and Administrative Review Control System.

ABSTRACT

The Tenth Annual Research Symposium on Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste was held in Fort Mitchell, Kentucky, April 3 through 5, 1984. The purpose of the symposium was to present to persons concerned with hazardous waste management the latest significant findings of ongoing and recently completed research projects funded by the Municipal Environmental Research Laboratory's Solid and Hazardous Waste Research Division and the Industrial Environmental Research Laboratory's Energy Pollution Control Division.

This volume is a compilation of speakers' papers and poster presenters' abstracts for Session A, Hazardous Waste Land Disposal. Areas covered are: 1) Remedial Action, 2) Pollutant Assessment, and 3) Pollution Control. Subjects include landfill design and operation, waste leaching and analyses, pollutant migration and control, waste modification, surface impoundments, technology assessments, remedial action techniques, and cost/economics.

This document covers hazardous waste land disposal only. A separate document for Session B, Hazardous Waste Incineration and Treatment, will be published by the Industrial Environmental Research Laboratory.

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CURRENT RESEARCH ON LAND DISPOSAL OF HAZARDOUS WASTES

Norbert B. Schomaker, Douglas P. Doerr
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

ABSTRACT

The Solid and Hazardous Waste Research Division (SHWRD), Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, in Cincinnati, Ohio, has responsibility for research in solid and hazardous waste management with respect to land disposal of wastes. To fulfill this responsibility, the SHWRD is developing concepts and technology for new and improved systems of solid and hazardous waste land disposal; is documenting the environmental effects of various waste disposal practices; and is collecting data necessary to support implementation of disposal guidelines mandated by the "Resource Conservation and Recovery Act of 1976 (RCRA)" PL 94-580. Also, SHWRD is collecting data on existing construction technologies and applying these techniques to the containment of pollutants emanating from uncontrolled dump sites. This is being done to assist in the implementation of the "Comprehensive Environmental Response, Compensation and Liability Act of 1980" (CERCLA) PL 96-510. This paper will present an overview of the land disposal aspects of the SHWRD Hazardous Waste Program Plan and will report the current status of work in the following categorical areas:

A. LANDFILLS
   1. Pollutant Generation
   2. Pollutant Movement
   3. Pollutant Control
   4. Pollutant Treatment

B. LANDFILL ALTERNATIVES
   1. Surface Impoundments
   2. Underground Mine Disposal

C. UNCONTROLLED SITES/REMEDIAL ACTION

D. COST/ECONOMIC ASSESSMENT

INTRODUCTION

The waste residual disposal research strategy, encompassing state-of-the-art documents, laboratory analysis, bench and pilot studies, and full-scale field verification studies is at various stages of implementation. Over the next 2 years the research will be reported as guidance documents for user communities. The waste disposal research program is currently developing and compiling a data base for use in the development of guidelines and standards for waste residual disposal to the land as mandated by the "Resource Conservation and Recovery Act of 1976" (RCRA). The RCRA Guidance Documents which will present design and operating specifications which the Agency believes comply with design and operating requirements and the closure and post closure requirements contained in Part 264 of the regulations are currently being prepared by the Office of Solid Waste in Washington, D.C. Technical Resource Documents (TRD) in support of the Guidance Documents are also being prepared by the Office of Research and Development in specific areas to provide current technologies and methods for evaluating the performance of the applicants' design. A separate paper entitled "Technical Resource Documents for Hazardous Wastes" has been accepted for publication in these proceedings. Therefore, no specific discussion of the TRDs will be presented in this paper.

Current hazardous waste land disposal research has been divided into four general areas: (a) Design Considerations for Current Landfill Disposal Techniques; (b) Alternatives to Current Landfill Disposal Techniques; (c) Remedial Action for Minimizing Pollutants from Uncontrolled Sites; (d) Economic Assessment of Hazardous Waste Disposal Practices and Alternatives.

The waste residual research program has been discussed in the previous nine symposia. These symposia describe the land disposal of both municipal and hazardous waste. The report of the previous most recent symposium is entitled "Land Disposal of Hazardous Waste: Proceedings of the Ninth Annual Research Symposium" May 2-4, 1983, Fort Mitchell, Kentucky, (EPA-600/9-83-018) September 1983.

LANDFILLS

Pollutant Generation

The overall objective of this research activity is to address techniques for leaching a waste sample to obtain leachate similar to that which will occur when the waste is landfilled. A leaching procedure is being developed for use in determining which pollutants will be of concern in movement of leachates out of the landfill and for evaluating leachate treatment schemes in order to better develop pollutant control technology. A Technical Resource Document (TRD) entitled "Landfill and Surface Impoundment Performance Evaluation" (SW-869) reflects current state-of-the-art in this area and is available from the Government Printing Office (055-000-00233-9).

One completed effort (1)* developed detailed laboratory procedure for extracting or leaching a sample of solid waste so that the composition of laboratory leachate is similar to the composition of leachate from the waste under field conditions. This effort led to the publication of a public comment draft Technical Resource Document entitled "Solid Waste Leaching Procedure Manual" (SW-924). A subsequent study that compared batch and column procedures for waste leaching was completed in FY 1983.

A second ongoing effort (2) was the development of a two-dimensional surface drainage system evaluation model for hazardous waste disposal facilities. A Technical Resource Document entitled "Hydrologic Simulation on Solid Waste Disposal Sites" (SW-868) reflects the current state-of-the-art knowledge in this area and is available from the Government Printing Office (055-000-00225-8). In addition to the development of this model, a detailed evaluation of various designs was conducted to assist in the design of numerical performance information for cover systems after closure and for leachate collection systems. The completed first phase of this project includes four tasks: 1) evaluation of subsurface drainage system designs for establishment of numerical performance standards; 2) development of user oriented two-dimensional subsurface drainage system evaluation capabilities; 3) user support for the current version of the Hydrologic Simulation on Solid Waste Disposal Sites; and 4) documentation, report preparation, and technical coordination. It is anticipated that this effort will be published in a two volume report in May 1984 entitled "Hydrologic Evaluation of Landfill Performance (HELP) Model."

A third ongoing effort (3) is to assess the potential for waste settling and cover subsidence in hazardous waste landfills and to develop a predictive model for such subsidence. The approach uses classical consolidation and collapse theories adapted to the waste fill situation. Several actual sites have been visited to gather real data on waste landfill characteristics for input to the modeling effort. Several scenarios of waste emplacement (e.g., bulk vs. barreled waste) are being evaluated. The final report entitled "Assessment of Time

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*Parenthesis numbers refer to the project officer who is monitoring this effort and whose name is listed immediately following this paper. The project officer can be contacted for additional information.

Settlement/Subsidence Effects on Cover Systems" is expected to be published approximately March 1985.

Co-Disposal

The overall objective of the co-disposal activity is to assess the impact of the disposal of industrial waste materials with municipal solid waste. Since the environmental effects from landfilling result from not only the soluble and slowly soluble materials placed in the landfill but also the products of chemical and microbiological transformation. These transformations should be a consideration in management of a landfill to the extent that they can be predicted or influenced by co-disposal operations.

Initial efforts (4) involved a study of the factors influencing (a) the rate of decomposition of solid waste in a sanitary landfill, (b) the quantity and quality of gas and leachate produced during decomposition, and (c) the effect of admixing industrial sludges and sewage sludge with municipal refuse. Some of the factors under investigation are: varying moisture infiltration rates, the addition of pH buffering compounds, prewetting wastes and varying ambient temperatures. A combination of municipal solid waste and various solid and semi-solid industrial wastes were added to several field lysimeters. The industrial wastes which were added were: petroleum sludge, battery production waste, electroplating waste, inorganic pigment sludge, chlorine production brine sludge, and a solvent-based paint sludge. Concentrations of metals (e.g., iron, cadmium, and nickel) were higher in leachates from industrial waste co-disposal cells, but leachate strength as measured by COD, pH and alkalinity was similar for the copdisposal and municipal refuse control cells. Leachate quantities collected from six hazardous waste co-disposal cells and municipal refuse control cells indicates that co-disposal cells produce leachate at earlier dates than the control cells, and that the co-disposal cells retained less moisture for the duration of the study period. The chlorine production brine sludge exhibited higher peak concentrations and elevated leachate concentration histories.

Further efforts of this research program which are incorporated into the final report include expansion of applied forecasting techniques. A model is presented for predicting the initial concentration of leachate for selected parameters based on waste composition, rate of moisture addition, and other relevant variables. Testing for similarities of leachate production behavior by performing a cross-correlation analysis for parameter sets from the same cell as well as different combinations of cells is addressed. Also a statistical test is performed on selected leachate characteristics to discern differences in behavior among the co-disposal and municipal refuse cells. A final report entitled "Evaluation of Landfilled Municipal and Industrial Hazardous Waste" has been received and is currently being reviewed. Publication is expected October 1984.

A second completed effort (5) relates to the co-disposal of chemically treated and untreated industrial wastes in a municipal refuse environment. Large lysimeters were utilized to determine the difference in leachate quality. Untreated chlorine production brine sludge when co-disposed with municipal solid waste released significant quantities of Al, Cd, Cu, Cl, Hg, and Na. With chemically stabilized brine sludge, however, the mass release of metals and chlorides was significantly reduced. Co-disposal of electroplating waste with municipal solid waste results in no different leachate characteristics than municipal waste alone. Stabilized electroplating waste lost an equal or greater quantity of metals as untreated waste. pH changes may account for changes in pollutant mobility. The final report on "Chemically Stabilized Industrial Wastes in a Sanitary Landfill Environment" will be published approximately January 1985.

Pollutant Movement

The objective of pollutant movement work is to develop predictive relationships which can be used in the design and regulation of disposal facilities for municipal and hazardous solid waste to insure that any releases to the environment will not be detrimental.

Current research is intended to develop tools for designing soil liners that limit pollutant release to a predictable minimum. The application is primarily for landfills, but the information is also useful in design of soil liners for surface impoundments and in predicting the amounts of pollutants that will pass below the zone of incorporation at land disposal sites. The work is proceeding in two parallel phases. In the first, methods for predicting movement of liquid (leachate) are being developed and improved, and in the second, methods are being developed for predicting how well soil liners will remove pollutants from any leachate that seeps through the liner. Work is in progress on empirical predictive techniques using samples of wastes and soils from locations of specific interest. This approach appears to be the most promising in order to integrate the effect of waste and soil characteristics on pollutant retention processes. The precision and accuracy that will be achieved by this method remains to be determined.

One completed effort (1) examined the extent to which hazardous substances from specific industrial and flue gas cleaning (FGC) wastes would migrate into groundwater at disposal sites. Procedures for conducting such examinations have been developed. A sequential batch leaching/soil adsorption procedure was developed which provides information comparable to that obtained from soil column studies, but in a much shorter time. The results of this effort have been reported in several previous symposia proceedings; a complete report of the project entitled "Migration of Hazardous Substances in Soil" is being revised and will be published in June 1984.

A second completed effort (1) was the development and testing of numerical simulation models for predicting movement of solutes in saturated and unsaturated soils. The accuracy and computational efficiency of several existing and newly developed numerical schemes for solving flow and transport equations were compared. Additionally, a closed-form analytical model was developed for predicting the unsaturated hydraulic conductivity from available soil moisture retention data. Considerations in selection of numerical models, including the effects of soil types, flow regime and magnitude of soil solute interaction parameters are discussed in a final report entitled "Mass Transport in Saturated-Unsaturated Media" which is being prepared for publication in September 1984.

A third completed effort (1) was the development of user oriented models for predicting movement in soil as a basis for improving selection of sites for disposing of solid and hazardous wastes. Long term movement rates were correlated with soil and leachate properties to develop regression equations forming a basis for a simplified predictive tool. The work has been completed and a preliminary report entitled "Behavior of Cd, Ni, and Zn in Single and Mixed Combinations in Landfill Leachates" describing use of this tool in conjunction with soil column tests to predict solute movement in soil has been published in the Proceedings of the Eighth Annual Research Symposium on Land Disposal of Hazardous Waste. The final report is expected to be published in June 1984.

A fourth completed effort (1) studied vertical and horizontal contaminant migration of Zn, Cd, Cu and Pb at three secondary zinc smelting plants and one organic chemical manufacturing plant. Migration patterns were defined using soil coring and monitoring well techniques. Soil coring was determined to be an investigative tool, but not suitable by itself for routine monitoring of waste disposal activities. The draft final report of this study entitled "Field Verification of Toxic Wastes Retention by Soils at Disposal Sites" is being prepared for publication by the end of 1984. Additional information on the project is available in the Illinois State Water Survey Cooperative Groundwater Report No. 9 (1982) entitled "Retention of Zinc, Cadmium, Copper, and Lead by Geologic Materials."

A fifth completed effort (1) was the determination of the attenuation mechanisms and capacity of selected clay minerals and soils for hexachlorocyclopentadiene (HCCPD) and "hex" wastes. Also, effects of caustic-soda brine on the attenuation of solubility of HCCPD were researched. The development of a chemical model to predict HCCPD migration through soil was pursued. Mobility of HCCPD in soils was independently assessed by use of soil thin-layer chromatography and column leaching techniques. This study has been completed and the draft final report entitled "Assessment of Soil, Clay and Caustic-Soda Effects on Land Disposal of Chlorinated-Hydrocarbon Wastes" is being prepared for publication in November 1984. Additional information on the project is available in the Illinois State Water Survey Environmental Geology Note 104 (1983) entitled "Soil, Clay, and Caustic Soda Effects on Solubility, Sorption, and Mobility of Hexachlorocyclopentadiene."

A sixth completed effort (1) is looking at the categories of water movement that occur in connection with various types of land-based disposal systems. Methods of soil hydraulic conductivity determination and interpretation are discussed. The results of the effort are currently being prepared in the form of a Technical Resource Document entitled "Soil Properties, Classification, and Hydraulic Conductivity Testing" (SW-925). This TRD will be released by the Office of Solid Waste in FY 84 for public comment.

A seventh completed effort (5) has evaluated the effects of organic leachates on clay liner permeability, and procedures for rapidly testing these effects have been outlined. The initial results of this effort have been published in a report entitled "Effects of Organic Solvents on the Permeability of Clay Soils" (EPA 600/2-83-016) April 1983.

An eighth ongoing effort (1) is currently underway to determine how accurately the EPA Gas Movement Model predicts the maximum distance that methane gas will move through soils adjacent to landfills and how accurately this model will predict the relative effectiveness of control systems (e.g., trenches, wells, barriers) for minimizing methane gas movement. Methane movement was measured at three selected landfills. With data from each landfill, the model will be used to predict the maximum extent of methane movement. The measured and predicted methane movements will be compared, reasons for any differences analyzed, and the accuracy and effort of use for the model determined. At one of the landfills, active and passive control systems are being installed. The observed degree of control and that predicted by the model are being compared. The project has been completed and draft final report is being prepared.

A ninth completed effort (1) has resulted in establishment of guidelines for design of gas migration control devices for sanitary landfills. The migration control devices studied included trenches venting under natural convection, trenches with exhaust pumping, trenches with recharge pumping, barriers, hybrid systems consisting of a barrier with a pumped (exhaust or recharge) or unpumped trench on the landfill site, and pumped (exhaust or recharge) pipe vents. Computer codes developed under a previous study (i.e., Moore and Alzaydi, 1977; and Moore and Rai, 1977) were modified to incorporate pressure flow as well as diffusional flow. The results of this completed effort are contained in a draft final report entitled "Gas Controls Design Criteria" which is being revised for publication in September 1984.

An tenth ongoing effort (1) is concerned with developing a contaminant/soil interaction protocol. Work on this project will include the collection, evaluation, and testing of procedures for conducting batch adsorption studies with leachates and soils to determine the amounts of pollutants that will be retained by clay liners in disposal facilities. The results of this project will be put into a TRD entitled "Batch Soil Procedure to Design Clay Liners for Pollutant Removal" for use in designing and evaluating clay liners to limit pollutant release from landfills. Release for public comment is not expected until February 1985.

An eleventh ongoing effort (1) is concerned with developing a TRD entitled "Methods for Prediction of Leachate Plume Migration and Mixing." The project will address: 1) to what degree leachate concentrations will be reduced by mixing with ground water in the vicinity of waste disposal sites; 2) the direction of movement and shape of leachate plumes; and 3) the types of models that are appropriate for predicting movement of solutes in ground water. An interim report is now being revised for release by the Office of Solid Waste for public comment in July 1984.

A twelfth completed effort (6) has resulted in the development of a handbook designating state-of-the-art and innovative procedures and techniques for management of leachate plumes. Included are methods for priority use rankings based on site conditions, risk assessments, cost and long term applications. Leachate migration controls include barriers, groundwater pumping, subsurface drains, and innovative technologies. Plume dynamics and delineation are also included in this study. Factors that affect leachate plume movement and criteria for evaluating plume management alternatives are described. The final report entitled "Leachate Plume Management" is undergoing final review for publication in FY'84 by EPA's Center for Environmental Research Information (CERI) during the summer of 1984.

Pollutant Control

The overall objective of this research activity is to reduce the impact of pollution from wastewater disposal sites by technology that minimizes, contains, or eliminates pollutant release and leaching from waste residuals disposed to the land. The pollutant control studies are determining the ability of in-situ soils and natural soil processes to attenuate leachate contaminants as the leachate migrates through the soil to determine the effectiveness of soils as liner for landfills. Leachate collection systems are being investigated to develop better guidance procedures for the installation and utilization of this system in a landfill environment. The studies are also determining how various synthetic and admixed materials may be utilized as liners to contain and prevent leachates from migrating from landfill sites.

Natural Soil Processes: The attenuation by natural soil processes of pollutants from hazardous waste and municipal refuse disposal sites is being performed in the controlled lab studies previously discussed in the section on pollutant movement.

Leachate Collection Systems: The leachate collection system technology (7) is being studied to prepare guidance for the design, construction, inspection, maintenance, and repair of a leachate collection system near the liner and a granular layer in the final cover to minimize the potential for system failures. An ongoing project is concerned with those aspects of design, installation and use which bear directly or indirectly on the prevention and correction of malfunctions of these systems. A report entitled "Potential Clogging of Landfill Drainage Systems" (EPA 600/2-83-109) addressing the mechanisms which may cause failure of leachate collection and cap drainage systems has been previously prepared for the USEPA. This project will confirm that the mechanisms identified in these two reports are probable causes for failures of leachate collection systems. This project will also develop design and construction guidance for, identify and describe maintenance and inspection procedures for, and make repair recommendations for leachate collection and cap drainage systems. A final report entitled "Design, Construction, Maintenance Inspection, and Remedial Action for Leachate Collection and Cap Drainage System" is expected to be published in March 1985.

Liners/Membrane/Admixtures: The liner/membrane/admixture technology (5) has been studied to evaluate suitability for eliminating or reducing leachate from landfill sites of municipal or industrial hazardous wastes. An ongoing study (5) is being pursued to assess actual field procedures utilized in (a) preparing the support sub-base soil structure for liners and (b) placing the various liner materials common to projects requiring positive control of fluid loss. Information obtained to date includes: methods and equipment used to prepare the subgrade and to place the liner material; specific design and construction considerations; and special problems encountered during installation. The final report entitled "Case Studies for Lined Impoundments" is being prepared for publication in January 1985.

A second completed effort (5) was concerned with determining the soil requirements to act as bedding and protective covers for flexible membranes.

Experiments were conducted using a variety of flexible membranes, thicknesses and densities of base and sub-base sands and soils, and then trafficked employing three different vehicles representative of those used for landfill construction. A design manual, applicable to the majority of the country, will be developed which will provide a design engineer with the data necessary to determine the most economic soil requirements above and below a flexible membrane. The final project report entitled "Laboratory Model Studies Conducted to Determine Soil Bedding Requirements for Flexible Membranes" is being prepared for publication in the summer of 1984.

A third ongoing effort (5) responds to the need for support of the guidelines and hazardous waste criteria mandated under RCRA. This project has been designed to provide the EPA with data to enable annual revisions to the landfill liner TRD entitled "Lining of Waste Impoundment and Disposal Facilities" (SW-870) which is available from the Government Printing Office (055-000-00231-2). Furthermore, it will provide assistance in permit application evaluation, assessment of performance and expert testimony.

A fourth effort (5), now completed, was primarily concerned with the evaluation of specific technologies (chemical liners) for the disposal and recovery of sludges from the metal finishing industry. Specifically, this effort evaluated the use of three chemical liners, i.e., agricultural limestone, fly ash, and hydrous oxides of iron in minimizing the pollution potential from an electroplating sludge. Data have been developed for mass flux values. The final report on the assessment of chemical liners is being reviewed for publication in June 1984.

A fifth ongoing effort (5) provided for the long-term testing of liner materials. Bag and tub testing of various membrane materials exposed to hazardous wastes was used. One of the objectives of this work was to assess the movement of organic contaminants through membrane liners. Permeability testing of various membrane liners was also attempted. The study of membranes on rough surfaces was undertaken to determine their puncture resistance and creep over long periods of time. Also, evaluation of site-specific effects of hazardous waste disposal on the performance of polymeric liner is now being carried out along with field verification of laboratory testing methods of polymeric liners. The final report is not expected until April 1985.

A sixth completed effort (8) was concerned with innovative techniques for detecting and locating leaks in landfill liner systems. Flexible membrane materials have been used as liners for landfills and surface impoundments to inhibit fluids from contaminating surrounding water resources. The primary objective of this task was to develop a method to detect and locate leak paths in membrane liners. The three methods that were studied are Time Domain Reflectometry (TDR), the Acoustical Emission (AE) Technique, and the Electrical Resistivity (ER) technique. These methods were evaluated for their technical and economic feasibility. The tests were conducted in a one acre pond lined with HDPE and filled with water. The results of this effort will be published in three final reports entitled 1) "Methods for Locating Liner Failures" which is concerned with a literature search on all three methods; 2) "Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failings" which will discuss the results for TDR and AE techniques; and 3) "Electrical Techniques for Leak Detection in Landfill Liners" which will discuss the results of the ER technique. All three reports are expected to be published in September 1984.

The objective of a seventh ongoing effort (3) is to evaluate in-situ repairs to damaged membrane liners in hazardous waste impoundments and landfills. Two methods are being studied. One is to evaluate uncovering and patching the liner using cements and solvents. The second method is to inject a grout plug into the liner hole. An evaluation of the compatibility of grouts and cements with various chemicals that may be encountered in a real situation will be undertaken before either of the methods are tested. The final report is expected to be published in May 1985.

Pollutant Treatment

The overall objective of this research activity is to evaluate physical, chemical, and biological treatment processes for (1) treating landfill leachate once it has been collected at the landfill site and (2) treating the waste at the landfill site to render it non-leachable by means of chemical stabilization.

Leachate treatment is achieved by applying various concentration/ pretreatment schemes (such as activated carbon adsorption, resin adsorption, aerobic and anaerobic biological treatment, and stripping) to the leachate stream to achieve the desired effect in meeting discharge requirements. A Technical Resource Document entitled "Management of Hazardous Waste Leachate" (SW-871) reflects current state-of-the-art knowledge in leachate collection and treatment and is available from the Government Printing Office (055-000-00224-0).

Chemical stabilization is achieved by incorporating the solid and liquid phases of a waste into a relatively inert matrix which exhibits increased physical strength and protects the components of the waste from dissolution by rainfall or by soil water. If this slows the rate of release of pollutants from the waste sufficiently and no serious stresses are exerted on the environment around the disposal site, then the wastes have been rendered essentially harmless and restrictions on siting will be minimal. A Technical Resource Document entitled "Guide to the Disposal of Chemically Stabilized and Solidified Waste" (SW-872) reflects current state-of-the-art knowledge in the area of chemical fixation and is available from the Government Printing Office (055-000-00226-6).

Another task involves the development of encapsulation systems (8) for hazardous waste drums. Additional work includes evaluating problems associated with stabilization/fixation technologies for conditioning waste with high liquid content prior to ultimate disposal. A final report is expected approximately February 1985.

LANDFILL ALTERNATIVES

Due to the concern for environmental impact and economics, alternatives to waste disposal in landfills and by incineration have been proposed. In this regard, SHWRD is actively pursuing research related to surface impoundments and underground mines and their applicability for the disposal of wastes.

Surface Impoundments

The temporary or permanant retention of liquid hazardous wastes in surface impoundments (i.e., pits, ponds, or lagoons) is an alternative to disposal in a landfill. Surface impoundments require special consideration to control volatilization into the air and SHWRD is conducting research in this area.

An ongoing effort (9) is investigating mechanisms of chemical movement of pollutants from surface and near-surface impoundments into the air. Methods for estimating air emissions of hazardous chemicals from waste disposal sites are being developed. These methods include transport coefficients and conceptual models for those coefficients not available. These methods can be used by facilities designers, permit writers or any other project reviewer to assess the impact of either existing or proposed facilities which involve the confinement of volatile chemicals for which there is some need to limit air emissions. A draft final report entitled "Emission of Hazardous Chemicals from Surface Impoundments to Air" has undergone review for publication in February 1985.

A second completed effort (5) is concerned with reviewing current designs and construction practices for disposal facilities. Geotechnical parameters which should be tested, observed, and documented during construction, operation and closure of disposal facilities will be identified. Disposal facility construction sites will be selected for observation of the procedures used in verifying the geotechnical data. This project will lead to the development of a manual on state-of-the-art testing procedures. The final report entitled "Geotechnical Quality Assurance in Construction of Disposal Facilities" has been prepared for publication in May 1984.

A third effort (4) addresses the potential and ongoing problems related to the operation and closure of new hazardous waste landfills and surface impoundments established in accordance with the Resource Conservation and Recovery Act (RCRA) and implementing regulations. In addition to documenting potential problems, the report document shall develop solution scenarios for dealing with each of the problem areas. Examina- tion shall include the following general areas: Liner systems (clay and synthetic); Leachate collection and detection systems; Waste effects; Cover systems (clay and synthetic), and gas production. The cost effectiveness of each corrective action and alternative measure shall also be addressed. The final report document will be a Technical Resource Document (TRD) entitled "Corrective Actions TRD for New Landfills or Surface Impoundments" and is expected to be published in the fall of 1985.

UNDERGROUND MINES

The use of underground salt mines for the long-term controlled storage of non-radioactive hazardous wastes has been shown to be promising as a result of studies by EPA and others and by the successful commercial operation of such a facility in West Germany since 1973.

A research program on characterization and containment of hazardous wastes for mine disposal was completed in 1977. This initial effort (8) included determination of suitable mine locations, determining waste handling requirements, specifying operational techniques, and the preliminary design of a mine disposal system. This material was used to develop a feasibility report entitled "Evaluation of Hazardous Waste Emplacement in Mined Openings" (EPA 600/2-75-040) December 1975. Based upon the feasibility report, a second effort (8) was initiated whereby one or more candidate mines was selected for further evaluation and detailed economic design was completed. A report entitled "Cost Assessment for the Emplacement of Hazardous Materials in a Salt Mine" (EPA 600/2-77-215) was published in November 1977. An engineering plan for an initial pilot-scale operation was developed and a full-scale demonstration was planned in cooperation with a private firm, but never implemented. A third effort (8) was initiated in FY 1983 to update these studies of hazardous waste disposal into underground mines. Updated information will include organizations involved and research or demonstrations being pursued, such as the use of a limestone facility. A final report is expected approximately September 1983.

UNCONTROLLED SITES/REMEDIAL ACTION

This program is designed to assist the Office of Emergency and Remedial Response, Regional Offices, states, and industry to meet the challenge of protecting the public from the damages of uncontrolled hazardous waste sites. Emphasis of the program is not to research new and novel technology, but to take "off-the-shelf" technology and adapt it to the uncontrolled dump site situation. Many existing technologies, such as those used in the construction industry, wastewater treatment, and spill cleanup, can be applied to uncontrolled waste sites. However, their application must be tested, cost and effectiveness determined, and limitations understood so that they may be effectively and economically utilized. It is a major function of this program to evaluate these techniques, combine techniques into cost-effective remedial systems, and provide those agencies responsible for remedial action with effective systems for the various situations found at uncontrolled waste sites.

A "Handbook for Evaluating Remedial Action Technology Plans" was published as EPA 625/2-82-006 in June 1982 as an initial summary of technologies which may be utilized at remedial action sites (10).

A field verification scheme (10) installed and monitored at the Connecticut MSW site was a surface capping technique. This study is now completed and the results will be published in a final report entitled "Remediation of an Inoperative Municipal Waste Landfill - Windham Landfill, Windham, Connecticut." The report is expected to be available May 1984.

A third completed (9) effort provides for a survey of ongoing and completed remedial action projects. Ten case study sites were selected and these sites visited and inspected for remedial action information. The results of this study are published in a report containing case study summary statistics of each of the sites investigated. The results of this completed effort were published in a final report entitled "Survey of On-Going and Completed Remedial Action Projects" (EPA-600/2-81-246) September 1981. This survey has been updated in a report entitled "Survey and Case Studies of Remedial Actions of Hazardous Waste Sites" and will be published in May 1984. This survey will continue to be updated periodically.

A fourth ongoing effort (1) is an investigation of the failure mechanisms and migration of industrial chemicals at a hazardous waste disposal site. The site has been closed and is under court order to be excavated for reburial elsewhere. During excavation of the landfill, the soil, facility, and waste conditions will be observed and samples are being collected. In the limited tests to date, field-measured hydraulic conductivity for several geologic units has been significantly greater than laboratory measured hydraulic conductivity using recompacted samples when the facility was designed. Pollutant migration appears to be concentrated in these units. Work is also underway on correlation of piping susceptibility (by the pin hole test) with observations of sinkholes and subsidence in trench covers. The final report of this task is expected to be published in June 1985.

A fifth effort (11) concerns evaluating the uses of geotextiles in stabilizing cover soils on landfills, acting as drainage layers for gases and liquids, and acting as bedding for membrane barriers. This program studied available geotextiles and geotextile products, their engineering properties, sizes available (length, width, thickness), chemical resistance, seaming techniques, relative cost, life expectancy, and specific potential usage. This project included an initial assessment of problems at the municipal refuse landfill site in Windham, Connecticut, and recommendations for those remedial measures in which geotextiles could play a significant role. The final report entitled "Evaluaton of the Use of Geotextiles for Landfill Cover Systems" will be published in April 1985.

A sixth ongoing effort (5) is concerned with determining the feasibility of retrofitting existing surface impoundments with an effective membrane liner system. This study evaluates one or more technically feasible retrofit liner installation techniques including the applicable liner candidate materials. The work assesses under which physical and chemical in situ conditions the various techniques will have the greatest chance for success. External equipment requirements, safety, and economics as well as overall limitation are being determined. Pilot-scale and field verification will follow the technical and economical assessment with the published report expected in January 1985. The data and procedures developed in this project will be used to update the existing TRD reports entitled "Lining of Waste Impoundment and Disposal Facilities" (SW-870) and "Closure of Hazardous Waste Surface Impoundments" (SW-873) available from the Government Printing Office (055-000-0231-2 and 055-000-00227-4).

The seventh ongoing effort (2) is concerned with the assessment of remedial actions for uncontrolled hazardous waste disposal sites. Work on this project will lead to two distinct products. The first is a detailed modeling program for site engineering assessment of remedial action alternatives at uncontrolled hazardous waste disposal sites. The second is simplified desktop procedures for remedial action alternative assessment based on the detailed modeling program. Both products will describe the effectiveness and cost of remedial actions considering site factors and characterization of control technologies. The draft reports entitled "Remedial Action Technology Evaluation Models for Uncontrolled Hazardous Waste Site, Volume I: Detailed Models" and "Volume II: Simplified Desktop Models" have been completed with anticipated publication in September 1984.

An eighth effort (2) is concerned with determining the effects of human safety and degree-of-hazard considerations on remedial action costs at uncontrolled hazardous waste sites. Cost components which are of a worker safety/degree-of-hazard nature will be identified. After identifying the component costs, specific cost figures will be determined. This information will be used to adjust total remedial action unit operation costs. The draft final report entitled "Cost Estimation Procedures for Remedial Action Technologies at Uncontrolled Hazardous Waste Sites" is undergoing review by the EPA regions and should be published in June 1984.

A ninth completed effort (12) is the demonstration of a block displacement technique to seal off large blocks of contaminated earth. This was proposed to include a combination of drilling and fracturing techniques, displacement through injection of a specially formulated bentonite slurry, and ultimate placement of a low-permeability material across the bottom and around the sides of the block. This project provides data which demonstrates the feasibility of placing a horizontal stratum of pumpable material at a reasonable subsurface depth in a region of favorable geology. Problems associated with unknown geologic materials and the interrelationship with slurry injection technology were identified, serving as a significant data base upon which further practice can be more accurately predetermined. The field construction within this project has been completed and the report entitled "The Block Displacement Method Field Demonstration and Specifications" is undergoing revision for publication in September 1984.

A tenth completed effort (6) has developed methods for classification of wastes by chemical and/or reactive properties and lays out a logical sequence of activities to determine the compatibility of two wastes. The test scheme includes a (1) field test kit, (2) manual containing flow diagrams and test procedure, and (3) mixing device. Simple and rapid field tests to determine reactive properties, chemical class, generic name and results of mixing are described. The testing protocol was challenged with 60 compounds and mixtures in the laboratory. It was field tested using 29" real world waste samples. Laboratory observation of 755 samples resulted in 15 false positives and 2 false negatives. The report entitled "Design and Development of a Hazardous Waste Reactivity Testing Protocol" is undergoing final review for publication in August 1984.

An eleventh completed effort (13) was a study conducted to determine the known information on the compatibility of grouts with different classes of chemicals. The information in this study can be used as a basis for testing and selecting grouts to be used at specific waste disposal sites with various leachates and has been published in a report entitled "Compatibility of Grouts with Hazardous Wastes" (EPA 600/2-84-015).

A twelfth completed effort (12) is concerned with the development of a handbook for slurry trench cutoff wall design, construction, and performance evaluation. Among the factors being tested is the use of different bentonites and their reactivity to hazardous waste and leachates. A summary of major cost elements will also be presented in the handbook. This Handbook was printed as a Technical Transfer document in the Design Manual series published by EPA's Center for Environmental Research Information (CERI). The identification number is EPA 540/2-84-001, Slurry Trench Construction for Pollution Migration Control.

A thirteenth ongoing effort (6) is currently underway to develop a decontamination manual for EPA Headquarters program offices and regional Superfund programs as part of the restoration profile of Superfund sites. The manual will give guidelines on 1) the extent to which contamination of buildings, structures and construction equipment can be reduced or eliminated, 2) decontamination methods, 3) costs, 4) health hazards, and 5) availability of equipment/personnel for the detoxification procedures. Specific waste types found in contaminated buildings, structures and equipment at Superfund sites will be identified. Potential secondary impacts from the available and potential decontamination treatment methods will be evaluated in this study. Decontamination costs versus risk and projected ultimate site usage will be determined and evaluated. Methods for monitoring the success of the various procedures will be defined. The project report is scheduled for publication in May 1985.

A fourteenth ongoing effort (7) is concerned with the effectiveness of a slurry wall used as a remedial action at a hazardous waste site. This effort will be completed in three phases: Phase one will review and interpret the quality control data that was obtained during the construction of the slurry wall. An example of this is the data obtained from hydrologic conductivity tests run on the trench backfill material. Phase two is concerned with the integrity of the completed wall. Not only is it concerned with seepage of contaminants directly through the wall backfill itself, but additional leakage through anomalies in the wall. Several detection methods will be investigated to determine their value in locating the size and frequency of anomalies in the wall. Phase three will obtain direct evidence of wall performance including evaluation of seepage quantities and contaminant migration. The final report is not expected until April 1986.

A fifteenth effort (4) is to assess the feasibility of alternative uses of hazardous waste sites following remedial measures. Phase one is an information gathering phase which consists of reviewing current literature, data and technical reports; interviews with experienced personnel in the area of site remediation and reuse, and site visitations where reuse has been implemented. Phase two will focus on identifying relationships between site remediation and redevelopment activities that would need to be considered in future site planning/decision making of specific hazardous waste sites. The final report entitled "Feasibility of Site Usage Following Hazardous Remedial Actions" is expected to be published in June 1985.

A sixteenth ongoing effort (11) is the development of a handbook to provide guidance for the evaluation, selection, and use of solidification/stabilization technology as a remedial action alternative at uncontrolled hazardous waste sites. The planning for the application of solidification/ stabilization is divided into two phases: process selection and scenario selection. Process selection is concerned with the chemistry of the solidification/stabilization process. A major problem with solidification/stabilization processes is the identification of the composition of the waste. Presented in the handbook are testing and analysis techniques for characterizing waste as a basis for selection of pretreatment and stabilization/solidification processes. Also data are developed on the compatibility of additives and specific classes of waste, and testing systems for the evaluation of stabilized/solidified wastes are reviewed. Scenario selection is concerned with the development of equipment requirements, construction sequencing, and cost estimating for the chosen solidification/stabilization process. The handbook will present, based on field surveys, four basic field scenarios that have been used successfully. A draft final report entitled "Technical Handbook for Stabilization/ Solidification Alternatives for Remedial Action at Uncontrolled Hazardous Waste Sites" has been prepared with anticipated publication in November 1984.

A seventeenth effort (11) is concerned with the development of a handbook which can be used as a guidance document for the selection, design, installation, and long-term maintenance of covers as remedial actions. This handbook entitled "Technical Handbook for Design and Construction of Covers for Uncontrolled Hazardous Waste Sites" will provide technical information for regulatory personnel as well as guidance for cover-system designers and construction engineers, and is expected to be published in November 1984.

Under an eighteenth task (13) which is being carried out, the compatibility of various chemicals with several grouts is being tested to determine any adverse effect with setting and durability. Promising grouts will be evaluted in field tests. Publication of the final report will not take place until June 1985.

COST AND ECONOMIC ASSESSMENT

The cost and economic activities are focusing on remedial action cost estimation, cost-effectiveness procedures, and economic issue evaluations related to CERCLA. Although few specific cost studies are conducted in the RCRA program, much cost information is included in many land disposal technology reports. The emphasis on remedial action issues generally reflects the crucial concern that the selected remedial action alternative be the most cost-effective as mandated by CERCLA.

One on-going effort (2) analyzed unit operations cost data for long term remedial action programs at uncontrolled hazardous waste sites. The analysis included an outline of the process for costing remedial action unit operations and combining the unit operations to yield relative cost data for an entire remedial action scenario. The final report entitled "Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites" (EPA 600/2-82-035) is available. A continuation effort is evaluating the effects of human safety and degree-of-hazard considerations on remedial action costs. This information has been incorporated into the report entitled "Survey and Case Studies of Remedial Actions at Hazardous Waste Sites"

A completed second effort (2) is a cooperative agreement involving economic, institutional and policy assessment related to CERCLA. The development of a legislative index of major implementation issues related to CERCLA has been completed and has been published by the Office of Emergency and Remedial Response. This report is entitled "Superfund; A Legislative History" and is available from the Environmental Law Institute. Analysis of actual remedial action costs based on case histories is the major ongoing activity.

The principal objective of a third completed effort (2) was to develop an analytical framework for conducting cost-effectiveness and reliability evaluations of remedial options at uncontrolled hazardous waste sites. CERCLA requires that remedial actions to be implemented under Superfund must be cost-effective. This is defined in the National Contingency Plan as "the lowest cost alternative that is technologically feasible and reliable and which effectively mitigates and minimizes damage to and provides adequate protection of public health, welfare, or the environment." A methodology for making determinations of cost-effectiveness will be developed and a guidance document describing the application of the framework will be prepared, which can be used by EPA and state regulatory personnel to aid in consistent and comprehensive evaluation of the factors affecting reliability and cost-effectiveness of remedial actions. A draft report entitled "Guidelines for Conducting Cost Effectiveness Evaluations at Uncontrolled Hazardous Waste Sites" has been prepared and should be published in the summer of 1984.

CONCLUSIONS

The laboratory and field research project efforts discussed here reflect the SHWRD effort in hazardous waste disposal research which has developed a sufficient data base to warrant presentation. Some of the projects will be discussed in detail in the following papers. More information about a specific project or study can be obtained by contacting the project officer referenced in the text. Inquiries can also be directed to the Director, Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, 26 West St. Clair Street, Cincinnati, Ohio 45268. Information will be provided with the understanding that it is from research in progress and the conclusions may change as techniques are improved and more complete data become available.

PROJECT OFFICERS

All the Project Officers can be contacted through the Solid and Hazardous Waste Research Division (SHWRD), whose phone numbers are listed below and whose address is shown above.

1. Dr. Mike H. Roulier, 513/684-7795

2. Mr. Douglas C. Ammon, 513/684-7875

3. Mr. Robert P. Hartley, 513/684-7836

4. Ms. Norma M. Lewis, 513/684-7836

5. Mr. Robert E. Landreth, 513/684-7836

6. Ms. Naomi P. Barkley, 513/684-7875

7. Mr. Jonathan G. Herrmann, 513/684-7836
8. Mr. Carlton C. Wiles, 513/684-7795
9. Mr. Stephen C. James, 513/684-7875
10. Mr. Donald E. Sanning, 513/684-7875
11. Ms. Janet M. Houthoofd, 513/684-7875
12. Dr. Walter E. Grube, Jr., 513/684-7836
13. Mr. Herbert R. Pahren, 513/684-7871

TECHNICAL RESOURCE DOCUMENTS FOR HAZARDOUS WASTES

Norbert B. Schomaker
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

ABSTRACT

The Environmental Protection Agency is preparing documents for permit officials responsible for hazardous waste landfills, surface impoundments, land treatment facilities and piles. The Technical Resource Documents (TRDs) describe current technologies and methods for evaluating the performance of the applicant's design in the areas of liners, leachate management, closure, covers, and water balance. These documents are basically a compilation of all research efforts of the Solid and Hazardous Waste Research Division (SHWRD) to date and are being published or developed to assist in the implementation of the regulations concerning hazardous waste disposal facilities. The RCRA Guidance Documents being prepared by the Office of Solid Wastes (OSW) will present design and operating specifications which the Agency believes comply with Design and Operating Requirements and the Closure and Post-Closure Requirements contained in Part 264 of the regulations. The information and guidance presented in these documents constitute a suggested approach for review and evaluation based on good engineering practices. There may be alternative and equivalent methods for conducting the review and evaluation. However, if the results of these methods differ from those of the Environmental Protection Agency's method, they may have to be validated by the applicant.

INTRODUCTION

Land disposal of hazardous waste is subject to the requirements of subtitle C of the Resource Conservation and Recovery Act of 1976. This Act requires that the treatment, storage, or disposal of hazardous waste be carried out in accordance with a permit. Owners or operators of new facilities must apply for and receive a permit before beginning operation of such a facility.

In reviewing and evaluating the permit application, the permit official must make all decisions in a well defined and well documented manner. Once an initial decision is made to issue or deny a permit, the subtitle C regulations require preparation of either a statement of basis or a fact sheet that discusses the reasons behind the decision, and becomes part of the permit review process specified in 40 CFR 124.6-124.20.

Eight TRDs have been completed to date. Six of the TRDs are related to landfills, and one document each is related to surface impoundments and land treatment. A listing of these documents is shown below, along with a brief description, publication number, and the project officer's name in parentheses.

TRD 1: EVALUATING COVER SYSTEMS FOR SOLID AND HAZARDOUS WASTE (SW-867) - This document presents a procedure for evaluating cover systems for solid and hazardous waste. It contains a checklist, with supporting documentation, that a permit writer can use to evaluate proposed cover systems.
*055-000-00228-2 (R. E. Landreth)

TRD 2: HYDROLOGIC SIMULATION ON SOLID WASTE DISPOSAL SITES (SW-868) - This document provides a computer package to aid planners and designers by simulating hydrologic characteristics of landfill covers to predict percolation as a

function of cover design and climate.
*055-000-00225-8 (D. C. Ammon)

TRD 3: LANDFILL AND SURFACE IMPOUNDMENT PERFORMANCE EVALUATION (SW-869) - The evaluation of leachate collection systems using compacted clay or synthetic liners to determine how much leachate will be collected and how much will seep through the liner into underlying soils is presented. The adequacy of sand and gravel drain layers, slope, and pipe spacing are also covered.
*055-000-00233-9 (M. H. Roulier)

TRD 4: LINING OF WASTE IMPOUNDMENT AND DISPOSAL FACILITIES (SW-870) - Information and guidance on liner systems is provided. The document discusses waste, liner types, compatibility, liner selection, specifications, design of leachate collection systems, and case study analysis methodology. It also includes a glossary of liner system related terms.
*055-000-00231-2 (R. E. Landreth)

TRD 5: MANAGEMENT OF HAZARDOUS WASTE LEACHATE (SW-871) - This document discusses leachate composition, leachate generation, selected management options, available treatment technologies, unit-treatment options, and system economics. It presents management options that a permit writer or hazardous waste landfill operator may consider in controlling and treating leachate.
*055-000-00224-0 (S.C. James)

TRD 6: GUIDE TO THE DISPOSAL OF CHEMICALLY STABILIZED & SOLIDIFIED WASTES (SW-872) - Basic information on stabilization/solidification of industrial wastes to insure safe burial of wastes containing harmful materials is presented. A summary of major physical and chemical properties of treated wastes is presented along with a listing of major suppliers of stabilization/solidification technology including a summary of each process.
*055-000-00226-6 (R. E. Landreth)

TRD 7: CLOSURE OF HAZARDOUS WASTE SURFACE IMPOUNDMENTS (SW-873) - The methods, tests, and procedures involved in closing a surface impoundment are discussed and referenced. Problems related to abandoned impoundments causing environmental degradation are discussed. Closure methods such as waste removal, consolidating the waste on site and securing the site as a landfill are also discussed.
*055-000-00227-4 (M. H. Roulier)

TRD 8: HAZARDOUS WASTE LAND TREATMENT (SW-874) - Land treatment medium, characteristics of hazardous waste, allowable waste loadings, facility planning for land treatment, land treatment permit processes, closure, and items to be considered during permit evaluation are discussed.
*055-000-00232-1 (C.C. Wiles)

Each of the completed TRDs is described in greater detail in the following section of this paper.

TECHNICAL RESOURCE DOCUMENTS CURRENTLY AVAILABLE

Evaluating Cover Systems for Solid and Hazardous Waste (SW-867)

A critical part of the sequence of designing, constructing, and maintaining an effective cover over solid and hazardous waste is the evaluation of engineering plans. This TRD presents a procedure for evaluating closure covers on solid and hazardous wastes. All aspects of covers are addressed in detail to allow for a complete evaluation of the entire cover system.

Covers may be evaluated for conformance to requirements for closure covers by the following eleven (11) general procedures in sequence:

1) examine soil test data,
2) examine topography,
3) examine climate data,

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*Drafts of the above documents have been released for public comment and all have been revised so as to incorporate the public's comments and reviews. They are currently being published and the reports will be available from GPO by requesting the stock number. Copies can be obtained for a price from the:

Superintendent of Documents
U.S. Government Printing Office
Washington, DC 20402
(202) 783-3238

4) evaluate composition,
5) evaluate thickness,
6) evaluate placement,
7) evaluate configuration,
8) evaluate drainage,
9) evaluate vegetation,
10) evaluate post-closure plan, and
11) evaluate contingencies plan.

This document describes current technology for landfill covers. For a landfill, these state that: 1) runoff that has touched hazardous waste must be collected and treated, 2) waste received must be analyzed, 3) each waste cell's contents, depth, location, and dimensions must be documented, and 4) a closure and post-closure plan is required to address control of pollutant migration, surface water infiltration, and erosion.

Guidance is provided on: characteristics and type of waste, location of fill with respect to potential environmental impact of pollutant migration, climate and precipitation, cover material and thickness, cover slope and vegetation, maintaining the final cover, maintaining groundwater, monitoring the gas collection system, and restricting access to the landfill. There are 36 specific steps, regarding the preceding factors, which should be followed in evaluating a permit for a cover for hazardous waste.

Hydrologic Simulation on Solid Waste Disposal Sites (SW-868)

Percolation and runoff of precipitation at solid waste disposal sites create a potential for ground and surface water contamination with leachate. The proper landfill site design and operational approach is to minimize or eliminate percolation through the solid waste and thus control the formation of leachate.

The purpose of this TRD is to provide an interactive computer program for simulating the hydrologic characteristics of a solid and hazardous waste disposal site operation. A large number of cities within the U.S. for which five years of climatic records exist have been put on tape for easy access and can be used in lieu of on-site measurements. In addition, the model stores many default values of parameter estimates which can be used when measured and existing data files are not available. The user must supply the geographic location, site area and hydrologic length, the characteristics of the final soil and vegetative cover, and default overrides where deemed necessary. From minimal input data, the model can simulate daily, monthly, and annual runoff, deep percolation, temperature, soil water, and evapotranspiration.

The model, which is a modification of the Soil Conservation Service (SCS) number method for predicting runoff and the hydrologic portion of the U.S. Department of Agriculture, Science and Education Administration (USDA-SEA) hydrologic model entitled "Chemicals, Runoff, and Erosion From Agricultural Management Systems (CREAMS)," has been modified to conform to the design characteristics of solid and hazardous waste disposal sites. The model takes engineering, hydrologic, and climatologic input data in the form of rainfall, average temperature, solar radiation, and leaf area indices and characteristics of cover material and performs a sequential analysis to derive a water budget including runoff, percolation, and evapotranspiration.

The user can specify up to three soil layers and may also specify a membrane liner at the base of the cover. The decreasing effectiveness of the liner is simulated. The model is designed for use in a conversational manner, that is, the user interacts directly with the program and receives output immediately. No prior experience with computer programming is required. All commands necessary to use the model are presented in the user's manual. The model can also be run in batch mode, which requires some computer programming experience.

Landfill and Surface Impoundment Performance Evaluation (SW-869)

This TRD describes how to evaluate the capability of various liner and drain designs to control leachate release. The author has allowed for the widely varied technical backgrounds of his intended audience by presenting, in full, the rigorous mathematics involved in reaching his final equations. Thus, any evaluator can take full advantage of the manual up to the level of his own mathematical proficiency.

This evaluation system considers the transport of liquids through simple modular configurations. The important parts of these modules are identified as the Liquid Transport Control (LTC) system, and the Diversion Interface (DI). The mathematics consider the efficiency with which the LTC and DI components convert leachate flow from vertical to horizontal. The extent of ponding on a bottom liner is considered in relation to the position and effectiveness of the drainage system.

The procedures described in the document should allow an evaluator to determine the adequacy of design for:

1) compacted clay liners or synthetic liners intended to impede the vertical flow of fluids,

2) sand or gravel drainage layers intended to convey liquids laterally into collection systems,

3) slopes on such liner systems, and

4) spacings of collector drains.

The evaluation procedure is independent of the structure of the regulation it supports. If regulations specify acceptable rates of release for leachate, or efficiencies of leachate collection systems, calculation results may be used directly to determine if the landfill is acceptable. However, if the regulations describe acceptable environmental impact, results from the evaluation procedure can be used as input for further evaluation in other manuals to determine if the impact of the landfill is acceptable.

Lining of Waste Impoundment and Disposal Facilities (SW-870)

This document provides information on performance, selection, and installation of specific liners and cover materials for specific disposal situations, based upon the current state-of-the-art of liner technology and other pertinent technologies. It contains descriptions of wastes and their effects on linings, a full description of various natural and artificial liners; service life and failure mechanisms; installation problems and requirements of liner types; costs of liners and installation; and tests that are necessary for pre-installation and monitoring surveys.

Described in the report are potentially useful lining materials and their associated technologies, including re-molded and compacted soils and clays, admixes, polymeric membrane liners, sprayed-on liners, soil sealants, and chemisorptive liners. The specific characteristics of these liners in service environments with various types of wastes are discussed, particularly with respect to compatibility with wastes, permeability to water and waste, failure mechanisms, and service life.

Design and construction of waste facilities with various types of linings are described, emphasizing installation of membrane liners and their problems. Special problems associated with the design and construction of solid waste disposal sites are considered. The subjects of leachate collection above the liner, gas control, and top-seals are addressed.

Several processes for selecting a specific liner or various satisfactory liners for a given disposal site are proposed. These include the use of compatibility tests, moderate duration exposure tests, soil conditions tests, costs, etc. Methods for the preparation of specifications covering the selected liners or groups of liners are suggested.

In the appendices, data are presented on liners and wastes, compatibility studies, manufacturers and suppliers, specifications, test methods, along with indices to lined disposal sites. As new technology is developed, and as experience in the use of liners becomes available, the manual will be upgraded on a chapter-by-chapter basis.

Management of Hazardous Waste Leachate (SW-871)

This document has been prepared to provide guidance for permit officials and disposal site operators on available management options for controlling, treating, and disposing of hazardous waste leachates. It discusses considerations necessary to develop sound management plans for leachate generated at surface impoundments and landfills. Management may take the form of leachate collection and treatment, or pre-treatment of the waste.

The manual addresses areas that must be considered in evaluating a leachate management option: leachate generation and composition, and available technologies for treatment of leachate and hazardous waste.

Leachate composition is examined for several hazardous waste landfills, synthetic leachates from lab studies, and sanitary landfill leachates. The expected composition of the leachate and the concentrations of the pollutants in the leachate are presented along with possible guidelines for permit writers to use in determining the relative hazards of a particular leachate.

A key section enumerates factors which influence treatment process selections and provides a suggested approach for systematically addressing each. Selected hypothetical and actual leachate situations are used as examples for applying the approach to the selection of appropriate treatment processes.

Other sections address monitoring, safety, contingency plans/emergency provisions, equipment redundancy/backup, permits, and surface runoff.

Guide to the Disposal of Chemically Stabilized and Solidified Waste (SW-872)

Stabilization/solidification of industrial waste is a pre-treatment process designed to insure safe disposal of wastes containing harmful materials. The purpose of this TRD is to provide guidance in the use of chemical stabilization/solidification techniques for limiting hazards posed by toxic wastes in the environment, and to assist in the evaluation of permit applications related to this disposal technology. The document addresses the treatment of hazardous waste for disposal or long term storage and surveys the current state and effectiveness of waste treatment technology. A summary of the major physical and chemical properties of treated wastes is presented. A listing of major suppliers of stabilization/solidification technology and a summary of each process is included.

This guide provides the background information needed for waste generators and regulatory officials to determine the testing program and/or product information necessary for them to make the best engineering judgements concerning the long term effectiveness in site specific conditions. Some familiarity with general soil characteristics, water balance, climatic conditions, and fundamentals of leachate generation would be helpful to the user.

Closure of Hazardous Waste Surface Impoundments (SW-873)

"Closure of Hazardous Waste Surface Impoundments" presents a listing of closure plan and post-closure care considerations and details for surface impoundments containing hazardous wastes. It is written primarily for staff members in EPA Regional Offices or state regulatory offices, who are charged with evaluating and approving closure plans for surface impoundments under regulations of the Resource Conservation and Recovery Act of 1976. Methods of assessing site closure considerations are documented.

The guide describes and references the methods, tests, and procedures involved in closing a site in such a manner that (a) minimizes the need for further maintenance, and (b) controls, minimizes, or eliminates, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, waste constituents, leachate, contaminated rainfall or waste decomposition products to groundwater, surface water, or the atmosphere. Problems that have been overlooked in abandoned impoundments and have caused environmental damage are discussed. The techniques involved are pertinent to closing an impoundment either by removing the hazardous waste or by consolidating the waste on-site and securing the site as a landfill. Technical criteria for implementing the closure, specifically those regarding aspects substantially different from a landfill, are given. Relevant literature or procedures are documented for more in depth review.

Hazardous Waste Land Treatment (SW-874)

The objectives of "Hazardous Waste Land Treatment" are to describe current technology and to provide methods for evaluating the performance of an applicant's hazardous waste land treatment facility design. Land treatment is approached comprehensively from initial site selection through final closure, and additional informational sources are referenced liberally. Land treatment, which involves using the surface soil as the treatment medium, is already widely practiced by some industries for handling their hazardous wastes. However, the lack of systematic study or monitoring of many past or present facilities has limited the knowledge and data base with regard to the important parameters and interactions. Additionally, many potentially land treatable wastes have not been tested or have been examined only under a limited range of conditions. Therefore, information is needed on site selection, waste characteristics, optimum soil and climatic conditions for degradation of organic constituents, application rates and scheduling decomposition products, and the contingency for environmental contamination. Potential problems include worker's health and safety, organic components, water pollution hazards, and local atmospheric emissions.

Land treatment of hazardous waste has not been under close scrutiny for a long enough period of time to acquire numerous documented failures resulting in environmental pollution. The potential for such failures due to the lack of proper design and/or management is evident from research conducted on the land treatment of other non-hazardous waste materials. For land treatment to be an effective system, the process must operate within a narrow range of parameters. Exceeding them could result in the uncontrolled release of pollutants to the environment.

FUTURE TECHNICAL RESOURCE DOCUMENTS

Additional TRDs now being developed or in planning stages by the Office of Research and Development:

A listing of these documents is shown below, along with a brief description and the project officers name in parentheses.

1. SOIL PROPERTIES, CLASSIFICATION AND HYDRAULIC CONDUCTIVITY TESTING

This report is a compilation of available laboratory and field testing methods for the measurement of hydraulic conductivity (permeability) of soils. Background information on soil classification, soil water, and soil compaction are included along with descriptions of sixteen methods for determination of saturated or unsaturated hydraulic conductivity. It is expected that the OSW will publish this TRD (SW-925) in April 1984 for public comment. Copies will be available through the Government Printing Office.
(M. H. Roulier)

2. SOLID WASTE LEACHING PROCEDURE MANUAL

This is a report on a laboratory batch procedures for extracting or leaching a sample of solid waste so that the composition of the lab leachate is similar to the composition of leachate from waste under field conditions. OSW will publish this TRD (SW-924) in April 1984 for public comment. Copies will be available through the Government Printing Office.
(M. H. Roulier)

3. BATCH SOIL PROCEDURE TO DESIGN CLAY LINERS FOR POLLUTANT REMOVAL

This project is studying the feasibility of using soil/leachate batch adsorption procedures for designing compacted clay liners to remove/retain known amounts of pollutants, and will contribute to information on designing and evaluating clay liners to limit pollutant release from landfills. The project will be completed in February 1985.
(M. H. Roulier)

4. METHODS FOR THE PREDICTION OF LEACHATE PLUME MIGRATION AND MIXING

This project has developed a variety of computer programs for hand-held calculators, microcomputers, and macrocomputers. The programs predict leachate plume migration from single and multiple sources. The document also contains discussions of sorption, case histories and a field study. A draft for public comment will be completed in July 1984.
(M. H. Roulier)

5. HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL

The original waste disposal site hydrologic model entitled, "Hydrologic Simulation on Solid Waste Disposal Sites" is being modified. This update will incorporate the two-dimensional aspects of landfill cover systems, as well as the addition of the leachate collection system. This second generation model will be entitled, "Hydrologic Evaluation of Landfill Performance (HELP) Model." It will be published for public comment in November 1984.
(D. C. Ammon)

6. DESIGN, CONSTRUCTION, MAINTENANCE, AND EVALUATION OF CLAY LINERS FOR HAZARDOUS WASTE FACILITIES

This project is collecting available information on construction and use of compacted soil liners, including test methods, chemical compatibility, failure mechanisms, performance of existing facilities, and field quality assurance and inspection to insure that the liner performs as designed. A poster paper on the work is being presented at this Symposium. The project is scheduled for completion in 1985.
(M. H. Roulier)

CONCLUSION

The TRDs that are being prepared by SHWRD are a series of documents which represent the Best Engineering Judgement (BEJ) for the design, operation, and closure of hazardous waste facilities. Eight documents have been completed with five more either in process or planned by the Office of Research and Development. These documents have been directed primarily for use by permit writers for evaluating facility designs and potential performance of new waste disposal facilities. The TRDs present the sum total of the body of information and experience gained by the Agency over the years on a given topic. As such, they contain factual summaries concerning the experience and effectiveness of design alternatives, covering what has been found not to work as well as what has been found to be effective. The TRDs can be considered as technical background or development documents supporting the RCRA guidance documents and regulations.

The project officers can be contacted by writing or telephoning the: U. S. EPA, Municipal Environmental Research Laboratory, Solid and Hazardous Waste Research Division, 26 West St. Clair Street, Cincinnati, Ohio 45268, Telephone (513) 684-7871.

CURRENT SHWRD PROGRAM IN SUPPORT OF SUPERFUND

Ronald D. Hill
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

ABSTRACT

The Solid and Hazardous Waste Research Division (SHWRD), Municipal Environmental Research Laboratory, has the responsibility for the control development program in support of "Superfund." The SHWRD research and development program has been organized to correspond with the "Superfund" legislation, i.e. the Oil and Hazardous Materials Spills Branch deals with removal actions (emergencies), and the Disposal Branch deals with remedial actions. The program is one of technology assessment to determine cost and effectiveness, adaptation of technologies to the uncontrolled waste site problem, field evaluation of technologies that show promise, development of guidance material for the EPA Office of Emergency and Remedial Response (OERR), technical assistance to OERR, and EPA Regional Offices.

The Removal Program is divided into three major areas of activity: (1) Personnel Health and Safety, (2) Demonstration of Equipment, and (3) Chemical Countermeasures. The remedial action program is divided into three major areas of activity: (1) Survey and Assessment of Current Technologies, (2) Field Demonstration and Verification of Techniques, and (3) Site Design Analysis. An overview of the removal and remedial program is presented.

INTRODUCTION

Within the EPA Office of Research and Development, the Solid and Hazardous Waste Research Division (SHWRD), Municipal Environmental Research Laboratory, has the responsibility for the control development program in support of "Superfund." The SHWRD research and development program has been organized to correspond with the "Superfund" legislation, i.e. the Oil and Hazardous Materials Spills Branch deals with removal actions (emergencies), and the Disposal Branch deals with remedial actions. Due to the special demands of "Superfund," the normal research and development process of concept development, laboratory evaluation, pilot testing, and field demonstration cannot be followed. "Superfund" is a 5-year program requiring answers today. Thus, our program is one of technology assessment to determine cost and effectiveness, adaptation of technologies to the uncontrolled waste site problem, field evaluation of technologies that show promise, development of guidance material for the EPA Office of Emergency and Remedial Response (OERR), technical assistance to OERR, and EPA Regional Offices. A brief overview will clarify our program goals.

Removal (Emergency) Actions

This program can be divided into three major areas of activity: (1) Personnel Health and Safety, (2) Evaluation of Equipment, and (3) Chemical Countermeasures.

Personnel Health and Safety

The goal of the personnel health and safety program is to develop protective equipment and procedures for personnel working on land or underwater in environments which are known or suspected to be immediately dangerous to life or health, so that such personnel can conduct operations related to investigating, monitoring, or cleaning up hazardous substances. In addition, it is hoped that this equipment and procedures will result in greater worker efficiency and lower operational cost, as well as improvement of personnel safety. Major outputs to come from this program are:

- Certification Report on EPA/Army-Developed, Long-Term, Self-Contained Chemical Protective Ensemble (FY'84)
- Report on Evaluation of Permeability of Chlorinated Polyethylene Protective Suit Fabric (FY'84)
- Manual of Procedures for Diver Safety in Contaminated Waters (FY'84)
- Manual on Decontamination Techniques for Specialized Cleanup Material Used During Emergency Response Operations (FY'85)
- User Manual for Selecting Protective Clothing Materials to Minimize Exposure to Highly Toxic Chemicals (FY'85).

Evaluation of Equipment

Our major effort on removal technology centers on evaluation of equipment designed for hazardous substances spill control and now adapted to removal action at uncontrolled dump sites. This equipment is being modified, adapted, and field tested. Examples of this equipment are the mobile incinerator, modular transportable incinerator, carbon regenerator, and soils washer.

Mobile Incineration System

SHWRD has developed a mobile incineration system designed for field use to destroy hazardous organic substances collected from cleanup operations at spills or at uncontrolled hazardous waste sites. EPA develops such equipment to actively encourage the use of cost-effective, advanced technologies during cleanup operations.

The mobile incineration system is designed to meet the requirements of TSCA and RCRA and provide state-of-the-art thermal detoxification of long-lived, refractory organic compounds, as well as debris from cleanup operations. Hazardous and toxic substances that could be incinerated include compounds containing chlorine and phosphorus--for example, PCB's, kepone, dioxins, and organophosphate pesticides, which may be in pure form, in liquids, in sludges, or in soils.

The mobile incinerator consists of four trailers with specialized equipment. (See attached Fact Sheet.) In the kiln, organic wastes are fully vaporized and completely or partially oxidized at 1800°F. Incombustible ash is discharged directly from the kiln, while off-gases are passed through the secondary combustion chamber (SCC) at 2200°F. Here, the thermal decomposition of the contaminants is completed. The flue gas exits from the SCC and is then cooled from 2200°F to approximately 190°F in a water spray quench elbow. Excess water is collected in the quench elbow sump, and the cooled gases then pass to the third trailer. Here, submicron particulates are removed from the gas stream as it passes through the cleanable high-efficiency air filter (CHEAF), and acid gases are neutralized in the mass transfer (MX) scrubber. Gases are drawn through the entire incineration system by an induced draft (ID) fan and are discharged from the stack. A monitoring system is used to analyze the flue and stack gases for combustion components [(carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2)], and emission components [(oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and total hydrocarbons (THC)] to ensure regulatory compliance and high thermal combustion efficiency.

To date the operational and performance aspects of the mobile incineration system have been evaluated during 37 days of shakedown and TSCA/RCRA compliance trial burn. The performance of the system has been exceptional in terms of destruction and removal efficiency (DRE) of test organics and the ability to meet air emission requirements. The DRE for test compounds, di-, tri-, and tetrachlorobenzenes, carbon tetrachloride, and PCB's ranged from 99.9991 percent to 99.9999 percent for all test runs (RCRA requirements, 99.99 percent). The combustion efficiency ($CO_2/(CO_2 + CO)) \times 100$ exceeded 99.999 percent for all tests (TSCA requirements, 99.9 percent). The removal of HCl produced from the combustion of chlorinated test compounds exceeded 99.88 percent (RCRA requirements, 99 percent). The emission rate of particulate matter was less than 80 mg/dscm, (RCRA requirements, 180 mg/dscm).

Now that the construction and initial testing of the mobile incinerator has been completed, it will be tested under field conditions. The EPA is currently considering various sites as candidates for the demonstration tests. These sites include: (1) Times Beach, Missouri, to demonstrate the detoxification of dioxin-contaminated soil by thermal incineration; (2) Kin-Buc landfill in Edison, New Jersey, to destroy 300 barrels of PCB-contaminated oily leachate; and (3) Hyde Park, New York, to demonstrate the thermal destruction of dioxin-containing sludges at a landfill site. After testing, the plans, specifications, and other information will be made available publicly for the purpose of encouraging commercialization of the new technology.

Modular Transportable Incineration System

A study has been initiated to determine the utilization of a modular transportable incineration system. The purpose of the study is to examine the technical, administrative, and economic feasibility of the use of modular incineration systems for destruction of toxic organic wastes at Superfund sites in the United States. Such wastes may include materials such as dioxins, organophosphate and carbamate pesticides, PCB's, and other organic substances recognized as highly toxic. The modular system would have a capacity 5-10 times the existing EPA Mobile Incineration System, and would be assembled from commercially available components (taking maximum advantage of existing equipment and technology) at a site selected to be within an economic transport radius of several sites needing cleanup. At the conclusion of cleanup operations, the system would be disassembled and moved to another location, thus avoiding public reaction to a permanent hazardous waste disposal facility.

This feasibility study will address the following major areas:

- System duty requirements, including examination of location and types of sites having incinerable wastes, and the characteristics of those wastes;
- Capabilities of existing transportable incineration systems, both domestic and foreign, specifically including systems currently being developed or operating in the Netherlands and Sweden. The potential for modification of domestic cement and lime kilns for use as incinerators is also to be evaluated;
- Effects of institutional requirements, such as RCRA and state permitting restrictions and examination of options for ownership (government vs. private sector);
- Process specifications, including examination of requirements for incinerating liquids and solids based upon the potential quantity of each;
- Cost analysis, including an examination of the effects of process selection, mode of transport (rail, barge, highway), capacity, energy requirements, and duration of operation;
- Comparison of the treatment requirements to the capabilities of existing facilities.

Carbon Regenerator

A trailer-mounted system for the on-site regeneration of "spent" granular activated carbon (GAC) is now undergoing shakedown tests.

Cleanup of hazardous materials from spills and abandoned industrial dump sites often involves the use of GAC which removes dissolved organic pollutants from water by adsorbing them on the carbon surface. The carbon and its accompanying load of contaminants must, however, be recycled or otherwise disposed of. One option is commercial regeneration of the carbon, in which the "spent" GAC is shipped to a central regeneration facility. In some situations--those involving highly toxic materials such as kepone or dioxins, for example--commercial regeneration is not practical because of the adverse public reaction to transporting such materials from one location to another. In such instances, on-site regeneration may be a viable alternative.

The mobile regenerator processes 200 lb of wet GAC/hr (equivalent to 100 lb of dry GAC). The carbon is screw-fed into a kiln that operates in a reduced air mode at a nominal 1800°F with a GAC-retention time of about 20 minutes. The atmosphere is conditioned with water to enhance reactivation of the GAC. The desorbed pollutants are partially combusted in the kiln and then ducted to a secondary combustion chamber (SCC) designed to totally decompose organics including organophosphates and chlorinated compounds. The flue gases are first quenched and subsequently scrubbed to remove acid gases. The hot carbon is quenched in water and is then available for reuse in a GAC contactor such as EPA's 200 GPM mobile physical/chemical treatment system.

All equipment is mounted on board the mobile unit. Propane or natural gas for the kiln oven SCC, fuel for the diesel generator, and scrubbing solution must be provided from external sources. The system can be powered by the onboard generator or from 440-volt AC mains. The unit houses the appropriate instrumentation and provides for emergency shutdown.

The load of pollutants that must be removed from the carbon and destroyed will approximate 10 percent of the dry weight of the carbon regenerated. Thermal capacity of the unit is about one million Btu/hr.

The regenerator has been shaken down and is currently undergoing controlled-condition tests. Field evaluation will probably take place in FY'85.

Mobile Soils Washing System

SHWRD has developed a Mobile Soils Washing System that can be used to treat excavated soils at sites where in-situ washing is ineffective or not applicable, and where hauling of excavated soil to a landfill is not cost-effective or is undesirable because of environmental or institutional barriers.

The system is capable of extracting contaminants from soils--"artificially leaching" the soil using a water-base cleaning agent--and thereby enabling operators to leave the treated soil on site. To accomplish this, the soil is passed through a rotating drum screen water knife soil scrubber where soil lumps are broken apart by intense jets of water, and chemicals are stripped from soil particles. The resulting soil slurry is fed into a four-stage countercurrent chemical extractor. Each stage consists of a mixing, froth-flotation cell connected in series with hydrocyclones which centrifugally separate solids from liquids. The soil particles are agitated repeatedly in washing fluid and are progressively decontaminated as they flow through each stage. The cleansed soil is then returned to the site. The extracted hazardous contaminants are separated from the washing fluid using physical/chemical treatment procedures (flocculation, sedimentation, carbon adsorption, etc.). The cleaned washing fluid is recirculated while the separated and concentrated contaminants are disposed of by appropriate means.

The Soils Washing System is capable of processing 4 to 18-yd^3 of contaminated soil per hour, depending on the soil particle size and the nature of the contaminant.

Current activity includes the shakedown of the system and complete full-scale, controlled-condition tests using water-based wash fluids to ensure that the system operates properly and performs within a delineated range of soil and pollutant parameters. Plans also call for an investigation of the feasibility of using the Soils Washing System with organic solvents to extract dioxin from wet excavated soils.

Chemical Countermeasures

One key countermeasure is the use of chemicals and other additives that are intentionally introduced into the open environment for the purpose of controlling the hazardous contaminant. The use of such agents, however, poses a distinct possibility that the release situation could be made worse by the application of an additional chemical or other additive. Therefore, the objective of this R&D activity is to define technical criteria for the use of chemicals and other additives at release situations of hazardous substances such that the combination of released substance plus the chemical or other additive, including any resulting reaction or change, results in the least overall harm to human health and to the environment.

The Chemical Coutermeasures Program (CCP) has been designed to evaluate the efficacy of in-situ treatment of large volumes of subsurface soils, and large, relatively quiescent waterbodies. For each situation, the following activities are planned: (a) a literature search to develop the body of existing theory and data; (b) laboratory studies on candidate chemicals at small scale to assess adherence to theory and define likely candidates for full-scale testing; (c) full-scale, controlled-condition, reproducible tests to assess field operation possibilities; and (d) full-scale tests at a site-of-opportunity. After the data are developed for a given chemical use situation, a technical handbook will be prepared.

To date, efforts have concentrated on soils-related activities and have taken this aspect of the program through the laboratory studies to a point where a decision will be made on continuation into full-scale, controlled-condition testing. The laboratory studies were used to determine whether significant enhancements to the in-situ cleanup of chemically-contaminated soils with standard water washing techniques could be obtained by using aqueous surfactants. The addition of the surfactant mixtures was designed to improve the solvent properties of the water and enhance the removal of adsorbed chemical contaminants.

Based on the results of the literature search, three pollutant groups (mixtures of compounds) were selected for laboratory testing on soils:

1. High molecular weight polynuclear aromatic and aliphatic hydrocarbons (distillation fraction of Murban crude oil)
2. PCB mixture in chlorobenzenes (Aroclor^R 1260 transformer oil)
3. Di-, tri-, and pentachlorophenols

Shaker table agitation studies were performed to determine the maximum cleanup efficiency under equilibrium conditions using water washes and a combination of 2 percent each of Hyonic PE90 (now known as NP90 by the manufacturer), and Adsee 799 (Witco Chemical) surfactants. After the most efficient surfactant concentrations were determined, column studies were initiated to evaluate soil cleanup efficiency under gravity flow conditions. In general, overall soil cleanup approaching the 90 plus percent level was attained with the intermediate molecular weight aliphatic and aromatic hydrocarbons, the PCB mixtures, and the chlorinated phenol mixtures. Results appear to support additional larger scale studies and plans are being discussed to construct a soils test facility at EPA's OHMSETT facility in New Jersey.

In the future, SHWRD would like to expand the controlled condition testing program to include the investigation of surfactants and other chemicals for decontamination of dioxin-laden soils.

Remedial Actions

We have divided the remedial action program into three major areas of activity: (1) Survey and Assessment of Current Technologies, (2) Field Evaluation and Verification of Techniques, and (3) Site Design Analysis.

Survey and Assessment of Current Technologies

We feel there is much to be learned from the remedial actions that have already been conducted by federal and state governments and industry. Thus, we have an ongoing and continuing effort to review and evaluate techniques that are being used and have been used in the past at uncontrolled hazardous waste sites. Our analysis includes defining the site-specific problem, determining the problems associated with implementing the technique, determining the effectiveness, and identifying the cost. We have found the data base on many of the early remedial actions to be inadequate for a good evaluation; however, those actions taken in the last few years are providing much better information. The survey results and the data used in our technical handbooks will be published on a regular basis. We hope to computerize this data base in the future. Major outputs in this area during FY'84 are:

- Report on the Survey on Completed and Ongoing Remedial Action Efforts
- Report on Cost-Effectiveness of Remedial Action Techniques

Field Evaluation and Verification of Techniques

Techniques that have a potential for being cost-effective are being field verified. These field evaluations are conducted in two ways. We will actually field test a technique that looks very promising or we will conduct an intensive field evaluation of a technique being installed as part of a remedial action. In practice, our research program provides the additional resources needed to obtain an array of operational monitoring data which will be adequate to fully evaluate and assess a technique.

Slurry Trenches

By this method, a trench is excavated using a bentonite and water slurry to support the sides. The trench is then backfilled with materials having a low permeability. The trench then acts as a barrier controlling the movement of water and waste materials. Slurry trench cutoff walls are considered to be a readily applied technique for confining contaminated groundwater by a vertical barrier. Two slurry trenches will be monitored for their effectiveness. The one at the Sylvester site in New Hampshire is of the soil-bentonite type and is 4000 feet long and has a depth varying from 40 to 90 feet. The wall surrounds a 20-acre hazardous waste site. The purpose of the wall is to prevent the ingress of water into the hazardous waste. The hazardous waste within the site is being pumped and treated. At the LiPari site in New Jersey, a soil-bentonite trench approximately 3000 feet long and ranging in depth from 30 to 52 feet will surround approximately 16 acres. The purpose of the wall will be to prevent the ingress of groundwater and the egress of contaminated water.

Isolation

The Block Displacement Method (BDM) is a new method proposed for complete in-situ isolation of contaminated earth materials. The method involves vertically displacing a mass of contaminated earth, and in so doing, placing an "impermeable" barrier at the bottom and sides of the mass. The barrier is formed by pumping slurry composed of soil, bentonite, or other suitable material into a series of notched injection holes. A perimeter separation is constructed using one of several techniques including thin slurry wall, vibrating beam, or a drill notch and blast technique. Once separation has occurred, the separation is surcharged with slurry to ensure a favorable horizontal stress field. The perimeter separation must be constructed at a slight angle inward toward the block center.

The bottom barrier is formed by drilling injection holes to a desired depth of the barrier below the waste. The base of the injection holes is then notched by slurry injection in a horizontal plane. Continued pumping of slurry under low pressure produces a large uplift force against the bottom of the block and results in vertical displacement of the block proportional to the volume of slurry pumped.

The BDM was field-tested near Jacksonville, Florida, in 1982. A block 60 feet in diameter and 23 feet deep was selected for the test. The site was located in uncontaminated ground adjacent to a contaminated site. The area was relatively flat and composed of marine sediment of silty sand in excess of 100 feet overlaying limestone bedrock. The groundwater level is normally 2 to 5 feet below the surface and a hard pan layer exists at a depth of approximately 20 feet. The perimeter separation was made using a notch and blast technique. Six-inch diameter holes were drilled on the perimeter at 6-foot intervals. Each hole was notched from top to bottom. Then an 18-inch, 5-foot high concrete forming tube was placed over each hole and filled with a high density slurry. All 32 perimeter holes were loaded with prima cord and blasted simultaneously. Connecting fractures were observed at the surface.

Within the circle, seven injection holes were drilled 23 feet deep and cased with 6-inch PVC pipe and cemented in place. Horizontal notches were cut at the base of the holes with a slurry jet notching tool. Slurry was then injected into the holes. Slurry connection between holes was observed after approximately 500 gallons of slurry had been pumped into the central injection hole. Once separation between holes was achieved, block displacement proceeded over a 2-week period by pumping approximately 2 yards per hour alternately into each injection hole. A resulting upward displacement of the block occurred.

In total, the block was displaced upward approximately 11 inches at its highest point and tilted approximately 1 degree from horizontal. A crescent-shaped portion of the block was sheared free of the upward-moving block and did not move significantly. The block area near the perimeter lagged the main portion of the block by 3-6 inches in upward displacement. The crescent-shaped shear zone and perimeter displacement lag were attributed to an incomplete fracturing and freeing of the block around the perimeter.

Thin-walled tube soil samples were retrieved and geophysical site surveys were conducted several weeks after the block displacement. Data collected indicated that the clay barrier material thickness generally corresponded to the measured upward displacement of the block of earth. Observations also suggested strongly that unexpected geologic details of the site interfered with accomplishment of the barrier placement exactly according to the design plan.

This field test showed that a bentonite clay slurry could be injected below a site and uplift would occur. The perimeter barrier construction technique used was unsatisfactory. Other perimeter construction methods should be used in this type of geologic material.

Drum Encapsulation

A prototype full-scale process and associated equipment have been developed and evaluated for encapsulating corroding 55-gallon drums of hazardous waste. The overpack system will provide a means for reducing the health and safety hazards associated with containing and transporting leaking 55-gallon drums and other containers or waste forms from an uncontrolled site to a final disposal site.

The overpack process utilizes friction-welding (spin-welding) to fuse a polyethylene (PE) cover onto a PE receiver into which a 55-gallon drum of waste has been inserted. Friction welding involves rotating one piece of plastic in contact with another stationary plastic piece. In the case of the overpack process, the cover is rotated while the receiver containing the waste is clamped in a stationary position. Friction causes the contact surfaces of both pieces to melt. Rotation is stopped and the pieces are pressed together. The melted polyethylene solidifies and the two pieces are fused together, creating a seal. The overpacks are fabricated by rotomolding a 1/4-inch thick container from PE and sectioning the container into a receiver and cover.

The thickness of the overpack is controlled by varying the amount of powdered PE placed into the rotomolder. The top (cover) is designed with ribs to accommodate the spin-welding tool. The overpack is approximately 85 gallons in size and large enough to accept drums that may be partially deformed. The friction welding machine consists of a hydraulically-operated plate used to spin the PE cover. Other features include the appropriate hydraulics, valves, controls, switches, a platform, and features necessary to position and seal the cover to the container. One operator is required to man the machine during the welding operation. The equipment is designed to be easily transported from site to site. Appropriate fork lifts and other drum-handling equipment are required at facilities handling the drums and the overpack system. Overpacks are designed for easy stacking and can be handled with conventional drum-handling equipment.

Rotomolded PE overpacks have been successfully sealed using the friction-welding equipment. Sealed overpacks have been subjected to hydrostatic burst tests and have exceeded the performance of similar size metal drums. Specimens under tensile testing of the weld have failed at points other than the weld. Leach testing of the welded overpacks has shown that the containers are leak-tight. Details of the test results, including micrographic examination of the seals and crush testing, are available.

Additional expected performance data can be extrapolated from previous studies and from the fact that PEs and other plastics are well characterized. They provide a unique combination of excellent chemical stability, flexibility, and mechanical toughness. Expected mechanical performance of the overpack system can be increased by filling the void between the drum and the PE overpack. This can be done with sands, soil, absorbant, off-spec portland cement, or other inert material.

The value of the friction-welded seal is in its capability to remain leak-tight under stresses that will normally force conventional screw caps, clamps, and similar seals to break or open.

An evaluation of the overpack process is being planned to prove the equipment performance and the ability to produce a leak-tight seal. Approximately 85-100 drums of waste will be overpacked. Random samples will be subjected to testing to further evaluate the performance of the overpack system. Because of the requirement to process 85-100 drums, the equipment as designed and constructed is essentially full-scale. However, the evaluation will also point to design modifications that will improve the performance. One example is the operation of multiple spin-welding plates from a single unit. This would increase processing capabilities.

Data from the evaluation and previous encapsulation studies will provide sufficient information to make the plastic overpack process available for use in several ways. It was specifically conceived as a superior overpack to decrease the health and safety hazards associated with the containment, transportation, and disposal of leaking drums from uncontrolled sites. However, it has potential application as an acceptable long-term containment system for the disposal of hazardous waste from small quantity generators. Additionally, because of its superior seal, the system could be used for the safe, long-term storage of hazardous waste that might be recovered in the future.

Dioxin Soil Stabilization

The purpose of this study is to determine the effectiveness of generic processes for stabilizing soils to prevent the release of pollutants. Dioxin-contaminated soils from EPA Region VII, Missouri dioxin sites, will first be analyzed to determine dioxin concentrations. The soils will then be stabilized by the most promising processes. Leaching tests will then be conducted to determine the effectiveness of the stabilization processes. A follow-on field evaluation is planned.

Fugitive Dust

Current and innovative methods applicable for suppressing the spreading of contaminated dust from uncontrolled hazardous waste sites will be investigated. The most promising methods will be field evaluated. Dioxin-contaminated dust will be of primary interest.

Covers

Low permeability covers are placed over hazardous waste material to prevent the inflow of surface waters into the waste mass and to reduce the amount of leachate. Flexible membrane covers installed at Windham, Connecticut, and the LiPari landfill in New Jersey are being monitored for their effectiveness. The uses of geotextiles in stabilizing cover soils on landfills, acting as drainage layers for gases and liquids, and acting as a bedding for membrane barriers, also are being evaluated. This effort is assessing the available geotextiles and geotextile products, their engineering properties, sizes available, chemical resistance, seaming techniques, relative cost, life expectancy, and specific potential usage. This project included an initial assessment of problems at a waste site in Windham, Connecticut, and made recommendations for remedial measures in which geotextiles could play a significant role.

Injection Grouting

In theory it is possible to grout upgrade or downgrade or beneath or into a hazardous waste site. Grouting is used to control the movement of water or leachate and can be used to solidify a mass of waste and thus reduce its leachability. Problems could be expected when attempting to grout in the presence of hazardous-chemical wastes, leachates, or extreme groundwater chemistry. In many instances, it would be difficult or impossible to achieve a controlled set time needed to guarantee integrity. Little is contained in the literature on the resistance of grouts to chemical attack.

This project will provide the Agency with pilot scale tests to predict applicability of grouting to specific sites and expand the state-of-the-art to hazardous waste in-situ stabilization.

Leachate Treatment

The purpose of this project was to compile data on the performance of unit processes and process trains for the treatment of aqueous hazardous waste streams. Evaluations of technologies were then performed. The processes found to have the greatest potential range of applicability were biological treatment, chemical coagulation, carbon adsorption, membrane processes, and stripping. Following these evaluations, bench-scale studies were conducted using the aqueous waste streams from several sites.

Retrofitting of Liners

This project is concerned with determining the feasibility of retrofitting existing surface impoundments with an effective membrane liner system. The study will evaluate one or more technically feasible retrofitted liner installation techniques, including the applicable liner candidate materials. The work will assess under which physical and chemical in-situ conditions the various techniques will have the greatest chance for success. External equipment requirements, safety, and economics, as well as overall limitation, will be determined. Pilot-scale and field verification will follow the technical and economic assessment.

Permeable Treatment Barriers

This is a three-phase project that will develop criteria for evaluating the use of permeable materials as hazardous waste pollutant control mechanisms. The utility of such permeable materials as coal, fly ash, limestone, and other material will be addressed alone and in conjunction with other remedial action techniques.

Asphalt Encapsulation

Asphalt encapsulation techniques, consisting of mixing heated asphalt with a sludge material, are being considered as a treatment option. Coating (or microencapsulation) of the sludge particles would improve the leachate quality and could act to reduce the hazardous nature of some compounds in the sludge. Additional heating of the mixture could act to thermally degrade the compound, e.g. nitroaromatic and RDX compounds.

Research to date has included (1) an evaluation of existing asphalt encapsulation techniques for hazardous wastes, (2) an evaluation of alternative heating/mixing systems, (3) review of the properties of various asphalt products which may be used, (4) laboratory experiments on the temperature and holding times required for thermal breakdown of the various compounds present in certain sludges, and (5) preliminary design of a pilot mixer/heating system. Our first studies have been with a sludge containing trinitrotoluene (TNT), hexahydro-1,3-5-trinitro-1,3,5-triazine (RDX), and other nitroaromatics. A synthetic sludge with physical properties similar to the actual sludge will be used during the initial runs and during modifications of the pilot system. Actual lagoon sludge will be used in the field for the final testing.

Factors which are being evaluated include residence times required for both mixing and thermal breakdown, mobility of the hazardous system, safety considerations, batch feed vs. continuous feed designs, and through-put rates.

A preliminary study has been completed on the selection of an asphalt/sludge mixer. The two most promising mixers are the pug mill and static pipe. Final tests are being made to select a mixer for pilot studies.

A laboratory evaluation was conducted to assess the temperature and holding times required for breakdown of the nitroaromatics and RDX in sludge. This information is necessary to design the mixer system and to determine if thermal degradation occurs at temperatures below the flashpoint of available asphalts. A total of 17 heating tests was conducted, representing four temperatures (150, 200, 250, and 300°C) and four residence times (5, 10, 15, and 20 minutes) plus one sample heated for 2 hours at 100°C. The results, however, do indicate that thermal degradation of approximately 90 percent of the explosive and nitroaromatic compounds occurs at 250°C. The results are based solely on the heating of the sludge. Further testing will be required in order to determine whether various types of asphalt in combination with the sludge result in equally low levels of explosive and nitroaromatic compounds. These tests are underway. In addition, studies will be conducted on utilizing the asphalt encapsulation technique on other organic waste. Following these tests, pilot-scale evaluation will be conducted.

Site Design Analysis

Our third area is an outgrowth of the first two, that is, the development of technical handbooks to be utilized by the planners and designers of remedial actions. Below is a listing of the handbooks that have been prepared or are in progress:

- Remedial Action at Waste Disposal Sites - 6/82
- Reviewers of Proposed Hazardous Waste Remedial Actions - 9/83
- Fugitive Dust Control - 11/84
- Cover Design and Installation - 11/84
- Fixation/Solidification of Waste in Surface Impoundments - 11/84
- Decontamination of Buildings, Structures, and Construction Sites - 5/85
- Slurry Trench Design and Installation - 3/84
- Procedures and Techniques for Controlling the Migration of Leachate Plumes - 3/84

Details of some of the remedial action projects are included in these proceedings.

CONCLUSION

In summary, the EPA Office of Research and Development is attempting to respond to a critical need of the Superfund Program, i.e. reliable and cost-effective control technology. Never before has the need been so great for quick answers to complex problems. In the short run, we are being faced with utilizing well-recognized engineering techniques that have been used in the past for other purposes and must be adopted to the uncontrolled waste site problem. In many cases these techniques have not been applied to Superfund problems and only through their actual utilization can we determine their effectiveness, advantages, and weaknesses. In the long run, new and innovative techniques may come forth and take their place in our arsenal of weapons to clean up hazardous waste sites.

For those of you desiring more information on the removal program, please contact:

Mr. Ira Wilder, Chief
Oil & Hazardous Materials Spills Branch
SHWRD, MERL, Woodbridge Avenue
Edison, New Jersey 08837

If you wish more information on the remedial program please contact:

Mr. Donald E. Sanning
Solid & Hazardous Waste Research Division
26 W. St. Clair Street
Cincinnati, Ohio 45268

EPA

FACT SHEET

United States
Environmental Protection
Agency

April 1982

EPA's Mobile Incineration System for Cleanup of Hazardous Substance Spills and Waste Sites

EPA's Office of Research and Development has recently completed construction of a mobile incineration system designed for field use to destroy hazardous organic substances collected from cleanup operations at spills or at uncontrolled hazardous waste sites. EPA develops such equipment to actively encourage the use of cost-effective, advanced technologies during cleanup operations. Other systems, including two devices for treating contaminated soils, both after excavation and **in-situ**, are currently under development. Once an item of hardware is complete, it is tested under field conditions. After testing, plans, specifications, and other information are made available publicly for the purpose of encouraging commercialization of the new technology. Numerous systems, including a mobile water treatment unit and a mobile laboratory, have been completed and are now available commercially.

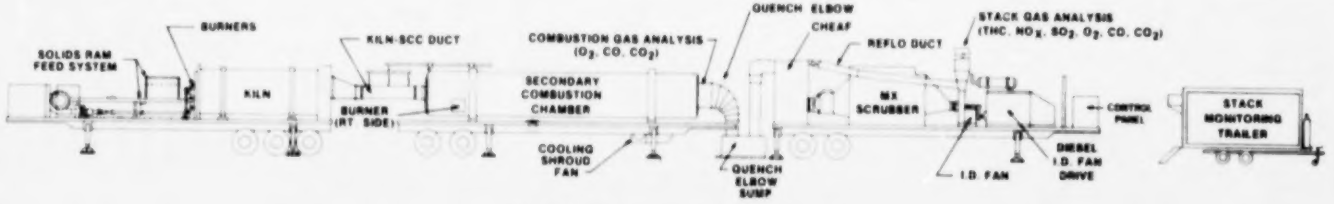
The mobile incineration system is designed to EPA's PCB destruction specifications to provide state-of-the-art thermal detoxification of long-lived, refractory organic compounds, as well as debris from cleanup operations. Hazardous substances that could be incinerated include compounds containing chlorine and phosphorus -- for example, PCB's, kepone, dioxins, and organophosphate pesticides, which may be in pure form, in sludges, or in soils.

The mobile incinerator consists of four trailers with specialized equipment (see illustration). In the kiln, organic wastes are fully vaporized and completely or partially oxidized at 1800°F. Incombustible ash is discharged directly from the kiln, while off-gases are pased through the secondary combustion chamber (SCC) at 2200°F. Here, the thermal decomposition of the contaminants is completed. The flue gas exits from the SCC and is then cooled from 2200°F to approximately 190°F in the quench elbow. Excess water is collected in the quench elbow sump. The gases then pass into the third trailer. Here, submicron particulates are removed from the gas stream as it passes through the cleanable high-efficiency air filter (CHEAF); acid gases are neutralized in the mass transfer (MX) scrubber. Gases are drawn through the system by an induced draft (ID) fan and are discharged from the stack. The monitoring system is used to analyze the flue and stack gases for combustion components [carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (0_2)], and emission components [oxides of nitrogen (NOx), sulfur dioxide (SO_2), and total hydrocarbons (THC)].

A 15-hour test burn with fuel oil has been completed, and the system has undergone priority modifications identified during this burn. The system is currently undergoing the final stages of preparation for a "PCB Trial Burn." The "PCB Trial Burn," scheduled during the summer of 1982, represents a systematic approach to evaluate and demonstrate the incinerator's ability to meet and exceed the performance requirements established by Federal, State, and municipal regulations. After the trials, the system will be demonstrated at several hazardous waste sites around the country.

To date (Spring 1982), EPA, through the Oil and Hazardous Materials Spills Branch at Edison, New Jersey, has spent $2.2 million on the design, development, testing, and permitting of the mobile incinerator. Fabrication costs of a similar mobile incineration system (without development and testing expenditures) is estimated to be $1.1 million.

For further information, contact Mr. Frank Freestone, Dr. John Brugger, or Mr. James J. Yezzi, Jr., Municipal Environmental Research Laboratory, Oil and Hazardous Materials Spills Branch, Edison, New Jersey. Telephone numbers are: (201) 321-6632 (commercial) or 340-6632 (FTS).



EPA MOBILE INCINERATION SYSTEM

DEVELOPMENT OF METHODS FOR IN-SITU HAZARDOUS WASTE STABILIZATION BY INJECTION GROUTING

Philip G. Malone and James H. May,
Geotechnical Laboratory,
and Robert J. Larson, Environmental Laboratory
USAE Waterways Experiment Station
Vicksburg, Mississippi 39180

ABSTRACT

Four grouting materials that might be employed in sealing hazardous waste sites to contain pollutants have been tested to determine their ability to perform in the presence of selected waste solutions simulating contaminated ground water. The waste test solutions were made up to contain a maximum of 10 percent by weight of the chemical compound being tested. Twelve chemical compounds typical of materials found in industrial waste leachates were included. Urethane and acrylate grouts were relatively easily retarded to the point where gelling did not occur. The most chemically-tolerant setting reactions were found in sodium silicate and portland cement grouts.

Samples of grout were exposed to the simulated waste solutions for 20 days. Sodium silicate and portland cement grouts proved to be the most durable.

Work is continuing on further evaluating the changes occurring in the grouted material in various chemical environments and in producing a continuous seal by injecting selected grout in closely-spaced holes in a sand test bed. Planning is underway for a field test for sealing coarse-grained materials.

INTRODUCTION

Hazardous waste disposal sites have often employed simple unlined pits or lagoons for the storage or disposal of liquid or semisolid wastes. Leakage from such unlined operations has been a source of ground and surface water pollution. Techniques for introducing liners or barriers for sealing hazardous waste lagoons have been proposed and cost/benefit studies have been conducted for selected techniques applied to specific sites. One of the most often proposed approaches for sealing bottoms of pits or lagoons has been the use of injectable grouts or sealants (1, 2, 3). Unfortunately, it is difficult to predict the effectiveness of these materials in an environment where wastes contain chemical contaminants that could potentially interfere with the grout setting reactions.

PURPOSE

The goals of the present investigation are to examine the ability of selected grouts to set, or gel, and remain stable when exposed to compounds that might commonly be present in hazardous waste. Selected chemically-tolerant grouts are being used in a test injection program to determine their ability to form a seal when injected in closely-spaced boreholes.

Most grouting materials are designed to be used in relatively clean natural waters and the bonding or setting reactions are sensitive to strong acids, bases, oxidizers, or organic solvents that can occur in pore water under and around a landfill. After setting the grouts must also exhibit stability and durability in what can be a chemically aggressive environment.

Grout seals or curtains are generally used with other hydrologic control strategies (such as counter pumping) because they are not considered to be impervious barriers. In a hazardous waste control system any contaminated water that is pumped must be treated or disposed of as a hazardous material. The ability of a grout to form a near-impervious barrier would greatly reduce the problem of water treatment when counter pumping is employed. Small-scale injection programs are being incorporated in this research program to learn more about the formation of continuous seals. The present report summarizes results to date and indicates areas of future activity.

APPROACH

Grout/Waste Gelling Studies

In order to evaluate the effects of waste in the setting or gelling of grout materials, masses of grout were introduced into beakers containing solutions of potentially interfering materials that could occur in industrial waste. Table 1 summarizes the type of grouts that were screened in this study and outlines their major properties. Each simulated waste solution was made up to fall within the concentration range that might be possible below a hazardous waste impoundment. Very soluble compounds were made up in 10 percent solution by weight in distilled water. Less soluble compounds were mixed vigorously with distilled water to produce a saturated solution. The characteristics of the waste solutions are given in Table 2. Baseline data on chemical grout set times were collected by mixing batches of grout using the manufacturers' specifications or standard mixes used in construction and allowing the material to set up in a paddle gelometer. Gel time determinations were made on 250 ml samples. Each sample was thoroughly mixed and placed in the gelometer at approximately 25°C. The gelometer blade rotates in the grout mix until a standard shear strength is reached and the paddle is held; the gelometer timer then stops and gel times can be recorded. The gelometer was adjusted to stop at the point at which the chemical grouts became too viscous to pour from the beaker. All gel times were determined in duplicate.

Gelling or hardening times for cement-based grouts were determined using a needle-penetration test system. An end point for penetration testing was selected based on the lack of pourability of the grout as its initial set. Final set was indicated when needle penetration was negligible. All gel time determinations were done in duplicate. The effects of waste on grout gelling were determined by mixing samples of each prepared grout with an equal volume of each simulated waste mixture. The gelling times were noted visually as the point where the material could no longer be poured. The gelometer was not employed because as gelling became very slow, the moving paddle would produce a cavity in the viscous grout and give a false indication of the actual set time.

Table 3 gives the normal set times for grouts with no interfering compounds present. Table 4 summarizes the effects of waste compounds on grout setting times. Changes in gelling time varied from a complete retardation of setting to the production of a flash or instantaneous set.

Grout/Waste Durability Studies

When grouts are injected at a waste site, the grouted material will have to withstand chemical attack from the migrating waste compounds. Grouting materials that interact with waste may not form permanent seals. To determine the resistance of chemical and cement grouts to chemical wastes, plugs of set grout were exposed to the simulated waste solutions (Table 2). Grouts and grout-sand mixtures were cast in 3.2 cm long by 2.5 cm in diameter cylinders or 3.2 cm cubes. The specimens were immersed for 20 days in the test waste solutions. Waste/grout interactions were determined by observing and measuring the dimensions of the specimens. Interactions could generally be classed as expansion, shrinkage, or no observable change. Results are summarized in Table 5.

TABLE 1. PROPERTIES OF GROUTS SELECTED FOR TESTING

Grout Type	Components	Usual Gelling Time (min)	Viscosity (cp)	Strength (gm/cm^2)
Acrylate	Acrylate monomer Methylenebisacrylate	0.1-1000	1.2-1.6	20-200
Portland cement	Portland cement Air entraining agents Fluidizers	--	--	--
Silicate	Sodium silicate Calcium chloride Magnesium chloride Dimethylformamide	0.1-3000	1.5-50	1-50
Urethane	Toluene Diisocyanate Acetone	0.08-120	20-200	NA

TABLE 2. CHARACTERISTICS OF WASTE TEST SOLUTIONS USED IN THIS STUDY

Waste Component	Character of the Waste	Concentration of Waste
Potassium Chromate	Oxidizer	10%
Hydrochloric Acid	Acid	10%
Ammonium Hydroxide	Base	10%
Sodium Hydroxide	Base	10%
Ammonium Chloride	Salt	10%
Copper Sulfate	Salt	10%
Benzene	Cyclic Hydrocarbon	Saturated
Gasoline	Hydrocarbon Mixture	Saturated
Oil	Hydrocarbon Mixture	Saturated
Phenol	Substituted Benzene	Saturated
Toluene	Substituted Benzene	Saturated
Trichloroethylene	Halogenated Hydrocarbon	Saturated

TABLE 3. NORMAL GELLING TIMES FOR GROUTS USING STANDARD GROUT FORMULATIONS

Grout Type	Gel Time (Average of Duplicate Runs)
Acrylate	30 seconds
Silicate (30% by wt.)	41.9 minutes
Silicate (50% by wt.)	25.2 minutes
Urethane	3.3 minutes
Portland Cement (Initial Set)	6.0 hours
Portland Cement (Final Set)	11.5 hours

TABLE 4. EFFECTS OF SPECIFIC COMPOUNDS ON GELLING TIMES FOR VARIOUS GROUT TYPES

Waste Compounds	Acrylate	30% Silicate Grout	50% Silicate Grout	Urethane	Portland Cement Initial Set	Portland Cement Final Set
Potassium Chromate	No Set	42 min	23 min	No Set	4 hrs	7.5 hrs
Hydrochloric Acid	No Set	4 min	Set on Contact	No Set	5 hrs	24 hrs
Ammonium Hydroxide	No Set	150 min	180 min	No Set	5 hrs	9.5 hrs
Sodium Hydroxide	No Set	No Set	200 min	No Set	3 hrs	7.5 hrs
Ammonium Chloride	5 min	Set on Contact	Set on Contact	No Set	--	24 hrs
Copper Sulfate	No Set	Set on Contact	Set on Contact	No Set	Set on Contact	24 hrs
Benzene	5 min	132 min	150 min	No Set	4.5 hrs	7.5 hrs
Gasoline (unleaded)	7 min	70 min	180 min	No Set	4 hrs	8 hrs
Oil	7 min	63 min	330 min	No Set	4.5 hrs	8 hrs
Phenol	No Set	3 min	Set on Contact	No Set	4.5 hrs	7.5 hrs
Toluene	84 min*	90 min	135 min	No Set	5 hrs	7.5 hrs
Trichloroethylene	7 min	114 min	180 min	No Set	3 hrs	7.5 hrs

* Partial set only.

TABLE 5. INTERACTION OF GROUT AND SIMULATED WASTE
AFTER 20 DAYS EXPOSURE

Waste Component	Grout Types			
	Acrylate	Silicate Grout	Urethane	Portland Cement
Potassium Chromate	SW (+83)*	SH (-88)	SH (-99)	NC**
Hydrochloric Acid	SH (-74)	NC	SH (-62)	NC
Ammonium Hydroxide	SW (+83)	SH (-80)	SW (+162)	NC
Sodium Hydroxide	SW (+83)	D	D	NC
Ammonium Chloride	SW (+70)	SH (-41)	SH (-42)	NC
Copper Sulfate	SH (-42)	NC	SH (-59)	NC
Benzene	SW (+76)	SH (-12)	SW (+83)	NC
Gasoline	SW (+70)	SH (-67)	SW (+70)	NC
Oil	SW (+109)	SH (-64)	SW (+54)	NC
Phenol	SW (+70)	SH (-4)	SH (-12)	NC
Toluene	SW (+83)	SH (-64)	SW (+319)	NC
Trichloroethylene	SW (+109)	SH (-80)	SW (+83)	NC

NC = No Change

SH = Shrink

SW = Swell

D = Dissolve

* Numbers in parentheses are the percent change in volume associated with the reaction.

** Slight surface etching.

Larger-Scale Testing of Grouts

Grouts that performed well in the bench-scale tests were evaluated on a larger scale. Ten to twenty liters of each grout were injected into 200-liter drums filled with sand and simulated waste solutions. Results of this testing confirmed the earlier compatibility testing and provided data on the sizes of typical grout pods (Figure 1).

A larger sealing test using silicate grout was performed in large (2 meter x 4 meter), metal, sand-filled carts. Grout was injected on 40-cm (maximum) centers on a grid pattern (Figure 2) to form a shallow, pan-like seal at a depth of 30 to 50 cm below the sand surface. The results of this testing will be used to evaluate the ability of the grout bulbs to coalesce to form a large sealed area. The results of the large-scale test are still being evaluated.

PROBLEMS ENCOUNTERED

No major experimental problems have been encountered in the evaluation of grouts for waste sealing. The screening has demonstrated that many grouts are ineffective in a hazardous waste environment. These are being eliminated from further testing.

RESULTS

Testing of grouts on a laboratory scale has shown that solutions simulating wastes in ground water can seriously alter the gelling time of the grouts or can completely inhibit gellation. Gelling of urethane grouts was completely inhibited by every simulated waste solution tested. Acrylates were inhibited by acids, bases, oxidizers, and copper sulfate. The most chemically-tolerant grouts were portland cement and silicate grout. Copper sulfate and ammonium hydroxide solutions produced flash sets with silicates and can complicate grout injection.

In the 20-day waste exposure testing, silicate grout and portland cement grouts showed the least interaction with the waste. Only one compound, sodium hydroxide, acted on and dissolved silicate grout. Sodium silicate is manufactured by reacting sodium hydroxide with amorphous silica to bring silica into solution, so this is a reaction that would be expected. Other simulated waste solutions caused shrinkage (probably by removing water from the gelled grout).

On the basis of testing performed to date, the most useful materials for sealing hazardous waste sites are silicate grouts and portland cement grouts. Portland cement grouts are particulate materials and have limited usefulness in fine- to medium-grained sediments. Silicate grouts are the (nonparticulate) chemical grouts best suited for possible use in sealing sediments containing or exposed to chemical waste. Testing done in this program has included only selected waste components and has not included combinations of wastes or very high concentrations of waste materials. Testing with ground water or leachate from the waste site may be required to demonstrate what grouts can be used at each site.

The test program is continuing with the evaluation of the large test grout bulbs and the pan-like horizontal seal. Field testing to produce an underseal at depth in sand material is being planned.

ACKNOWLEDGMENTS

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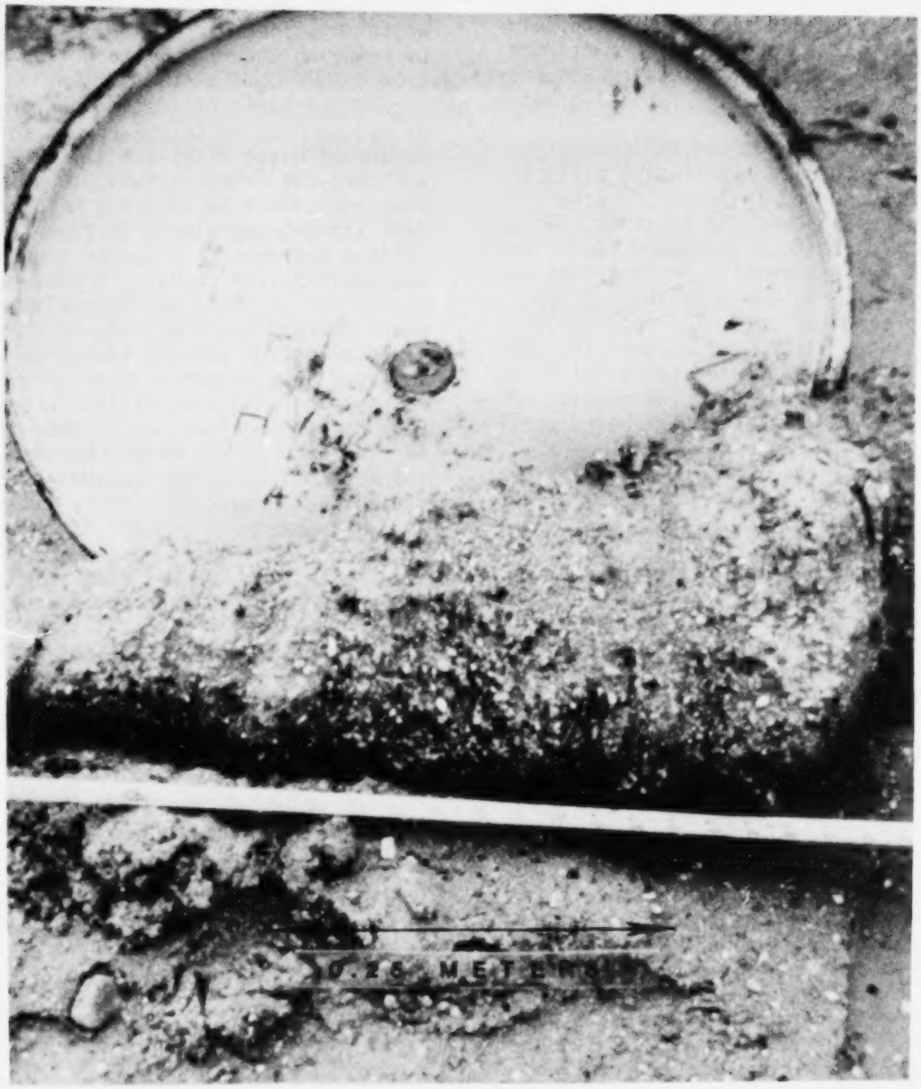

Figure 1. Photo of grout pod produced by injecting silicate grout into a 208-l drum filled with saturated sand.

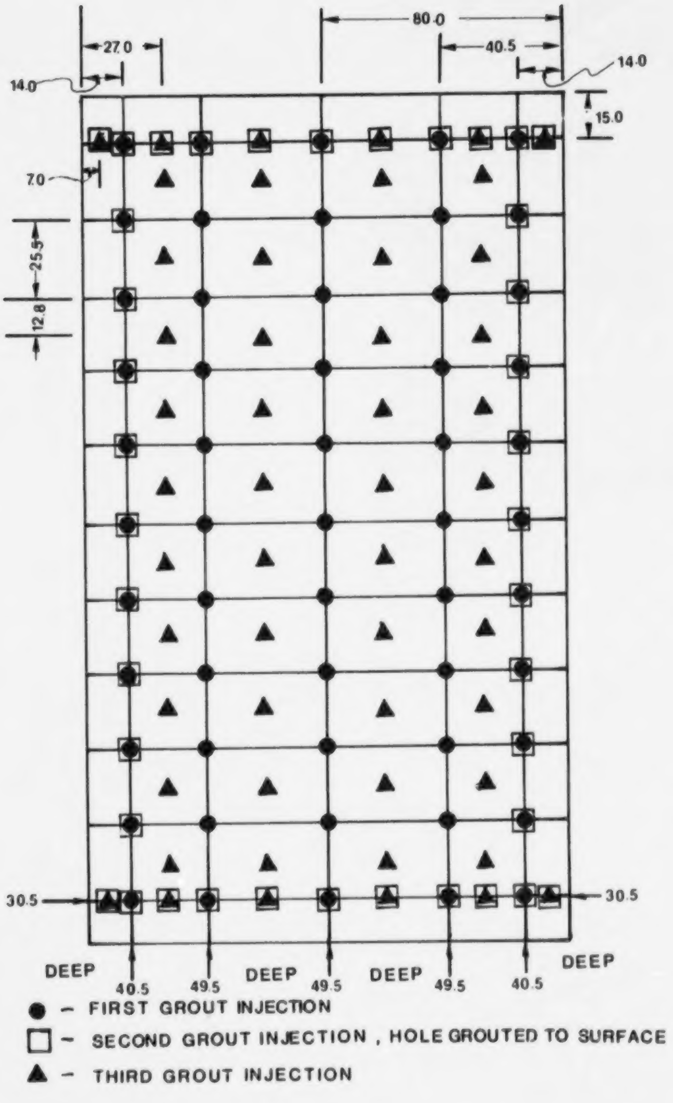
80.0
27.0
40.5
14.0
14.0
15.0
7.0
25.5
12.8
30.5
30.5
DEEP
40.5
49.5
DEEP
49.5
DEEP
49.5
40.5
DEEP
● – FIRST GROUT INJECTION
□ – SECOND GROUT INJECTION , HOLE GROUTED TO SURFACE
▲ – THIRD GROUT INJECTION

Figure 2. Layout of injection holes for producing a pan-like layer of grout. Each grout injection emplaces 7 liters of grout. All measurements are in centimeters.

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REACTIVITY OF VARIOUS GROUTS TO HAZARDOUS WASTES AND LEACHATES

Andrew Bodocsi, Issam Minkarah and Brian W. Randolph
University of Cincinnati
Department of Civil and Environmental Engineering
Cincinnati, Ohio 45221

ABSTRACT

Recent research on the permeability of clay liners used for hazardous waste landfills indicates that their permeability may increase considerably after they are permeated by various organic leachates. Concern over this has led to the proposal of grouting the soils surrounding such landfills as a remedial type of containment. At the present not much is known about the effects of hazardous leachates on the permeability of grouted soils. Procedures are presented for grouting test samples, and for testing the durability and the potential long-term permeability changes of grouted soil samples when permeated by hazardous chemicals.

INTRODUCTION

In recent years the long-term integrity of clay landfill liners has been questioned. It has been indicated that the permeability of liners may be increased by leaching of the hazardous wastes contained in these landfills (Anderson, et al., 1981 and 1982). Concern over these contaminants breaching the landfill liner and entering the groundwater, and subsequently potable water supplies, has led to several proposed methods of containment. Grouting the surrounding soil is one method being evaluated.

At this time nothing has been published concerning the effects hazardous leachates will have on the permeability of grouted soils. Theoretically, grouts can be injected to fill the soil voids, then gel (set) to create a continuous mass with a reduced permeability.

This paper outlines procedures for grouting soil samples and for evaluating the durability of these samples when subjected to toxic chemicals or leachates. Also presented are procedures for testing the long-term permeability of grouted soil samples when permeated by the hazardous leachates.

PURPOSE

The purpose of this research was to develop experimental procedures to test the long-term reactivity of grouted soil samples to hazardous chemicals or leachates. Specifically, procedures were developed to test the long-term changes in permeability of grouted soils when leached with hazardous chemicals. The methodology developed will be used in ongoing research into the feasibility of grouting for hazardous waste containment. Along with the permeability test procedures, other methods and devices also had to be developed: (a) a grouting apparatus and a grouting method to produce uniform and reproducible grouted soil samples; and (b) a permeameter device and two types of permeability test apparatuses.

APPROACH

The following sections outline the design of the experimental procedures, and the steps that were taken to select the materials, devices and methods to be used to test the reactivity of grouted soil samples to hazardous chemicals and leachates.

Selection of Materials, Devices and Methods to Produce Grouted Soil Samples

Time and cost factors preclude the testing of all commercially available grouts with the numerous chemicals and mixtures of chemicals possible in a hazardous waste landfill. Basic grout types will have to be tested though, with selected chemicals. Three representative grouts were chosen after a review of available literature. A sodium silicate grout was selected due to its long-term popularity. A urethane grout was chosen as a representative of the second largest group of chemical grouts in use. An acrylamide was selected due to its considerable use in the last decade (Karol, 1982).

Siroc 132, a product distributed by Raymond International, was selected to represent the sodium silicate grouts. CR 360, a product of the 3M Company, represents the urethane chemical grouts. AV-100 distributed by Avanti International, was chosen to represent the acrylamide family of chemical grouts. Two sands were chosen as representative materials to be grouted. A commercially available silica sand was selected for the urethane and acrylamide grouts. All portions passing the number 30 sieve (0.59 mm) of a Cincinnati area natural mason's sand was used in tests of the sodium silicate grout. The finer, better graded mason's sand was used due to the problem of syneresis in this type of grout, which can greatly reduce its effectiveness when used for liquid cutoff (Karol, 1982).

The soil samples are grouted in a 3 inch (7.62 cm) inside diameter plastic mold. Sample lengths can be varied as required, and several samples can be grouted in a single mold. The mold is made of 1/4 inch (0.64 cm) thick clear acrylic. Specifically, a 12 inch (30.48 cm) long grout cylinder is sawn longitudinally into two sections and a 0.125 inch (0.32 cm) diameter groove is machined down each face. Two 0.125 inch (0.32 cm) diameter rubber seals are placed in the grooves and five hose clamps are used to hold the cylinder together and compress the seals. Two aluminum endplates, each with a depressed center portion to accept the cylinder ends, are used as caps. A seal is provided by a rubber gasket at the top and bottom. Brass valves are fitted into the center of each endplate for introduction of the grout from below and metering and exhaust of the outflow at the top. The cylinder and endplates are compressed longitudinally with three threaded rods and wingnuts (See Figure 1).

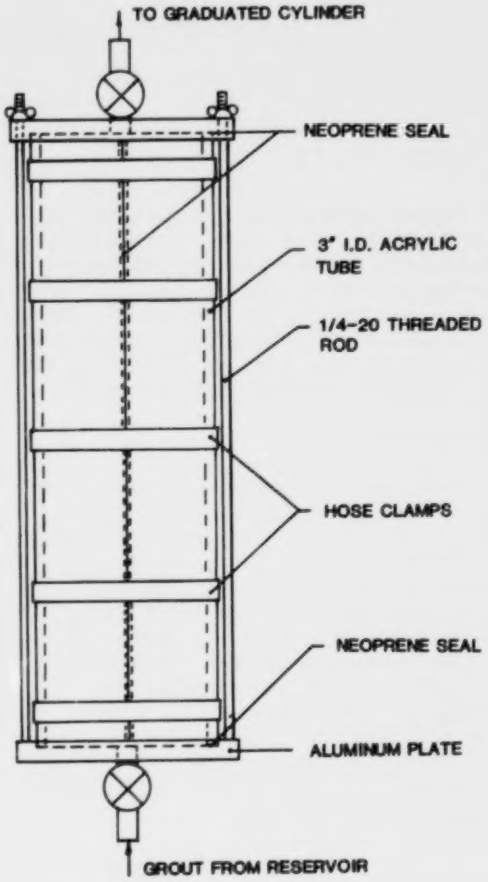

Figure 1. Grouting Mold.

To prepare the grouted soil samples, the chosen sand is dropped approximately eight inches from a funnel to form one inch (2.54 cm) lifts in the cylindrical mold. Each one inch lift is rodded with a 3/8 inch (0.95 cm) diameter rod 25 times, using care not to enter previously compacted layers. A round bar with an end area of 1.5 square inches is used to level out the top of the sand when the desired thickness is reached. Rigid, perforated plastic disks are placed at the top and bottom of each sample to ease separation and to provide flat and square ends. A lecithin mold releasing agent is sprayed on the inside of the mold to facilitate sample removal.

The pressure resistant mold is then capped and a carbon dioxide line is attached to the bottom of the cylinder. Carbon dioxide, being heavier than air, is passed through the sand at 10 psi (69 kPa) to displace all air from the voids. Excess air in the soil voids can affect the permeabilities and it is difficult to reproduce the same degree of saturation in many samples if all void air is not replaced by water.

Next, distilled, deaired and deionized water is passed through the carbon dioxide-saturated sand at 10 psi (69 kP) pressure from beneath. Forcing the gas ahead of it, the water takes on any remaining carbon dioxide in the pores to form a dilute carbonic acid, leaving the voids nearly gas-free and almost perfectly saturated with liquid. Six soil pore volumes of water are passed through the sample to displace the weak carbonic acid and flush it from the voids. The flow should be metered so that quick conditions do not arise in the sand.

At this point the grout vessel can be attached to the bottom of the mold and the liquid grout injected at a pressure and flow rate suitable for that grout mix and the chosen soil (See Figure 2). In order to replace all water in the voids, at least two soil pore volumes of grout should be passed through the sample before tightening the valves and starting the curing period. Curing typically requires two days in the mold, then seven or more days wrapped in plastic film in a controlled environment (at approx. 98% humidity and 20°C).

Selection of Test Method for Determining the Effects of Chemicals on the Durability of Grouted Soils

Although future testing will expose grouted samples to a myriad of hazardous chemicals and wastes, in this stage of experimental design only two classes of chemicals and a control liquid are used. These are: A) reagent grade methanol and reagent grade acetone, both neutral-polar organics, B) reagent grade xylene, a neutral-nonpolar organic, and C) distilled, deionized water, the control liquid. ACS reagent grade chemicals are used as an extreme case to tax the limitations of the grouts, apparatuses and procedures.

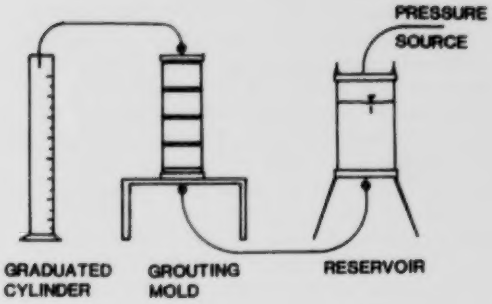

Figure 2. Schematic View of Grouting Apparatus.

To obtain the approximate reactivity of the grouted soils to leachates, immersion tests according to ASTM Standards, D 543, "Test for Resistance of Plastics to Chemical Reagents", were performed. To prepare the immersion coupons, the liquid grout was mixed with the sand by hand and placed in 1/4 inch (0.64 cm) layers in a 1.5 inch (3.81 cm) diameter tube, separating each layer with two filter papers. After 48 hours of curing in the mold, the samples were removed and placed in a controlled environment (approx. 98% humidity and 20°C) for four days before measuring, weighing and immersion in the chemicals. Then each specimen was placed in 150 ml of one of the three reagents. The samples were swirled and visually checked daily for seven days. After that, they were towel dried, weighed and measured. At this time, immersion tests have only been performed on the urethane and sodium silicate grouts.

Selection of Test Methods for Determining the Effects of Chemicals on the Durability of Hardware Materials Used in the Testing Program

The hardware used to grout and to conduct permeability tests on the samples has to be durable and resistant to attack from grouts and leachates. In order to ascertain reactivity data on specific potential materials with the chosen leachates, ASTM reactivity tests were conducted. ASTM Standards, D 543, "Test for Resistance of Plastics to Chemical Reagents" was used for all plastics and synthetic rubbers under consideration. ASTM Standards, G 31, "Standard Recommended Practice for Laboratory Immersion Corrosion Testing of Metals" was followed for all potential metals.

Selection of Devices and Test Methods for Determining the Effect of Chemicals on the Permeability of Grouted Soils

The objectives of the permeability tests in this project are to determine the permeability of grouted soil samples to distilled, deionized water, and to measure the changes of their permeability due to long-term exposure to various chemicals.

To run a permeability test on a grouted soil sample, two devices are needed: 1) a permeameter to encase the sample and confine the flow of the permeant and 2) a permeability test apparatus which provides for the channeling of the permeants into and out of the permeameter and allows the accurate measurement of flow through the sample.

Permeameters

Several different permeameters were designed and tried. One of the promising designs used a fixed-walled cylindrical mold to confine both the sample and the permeant flow. However, shrinkage of the grouted sample allowed the permeant to flow through the space between the mold and the sample and the permeability test results were erroneous.

The final version of the permeameter is of a triaxial design. In essence, the grouted sample is encased in a latex membrane, then placed and pressurized in a confining chamber filled with glycerine. Permeant is introduced to the top of the sample at a desired pressure but lower than the confining pressure. An even lower pressure may be applied to the tail end of the sample which can help reduce the volume of any gases trapped in the sample and thereby yield more accurate permeability values. The permeant that passes through the sample is collected at the bottom and is measured for permeability calculations. The confining chamber pressure applied to the membrane prevents the short circuiting of the permeant along the sides of the grouted sample.

Specifically, the sample is placed between two porous stones, then between two 3 inch (7.62 cm) diameter aluminum disks (base and cap) approximately 2 inches (5.08 cm) thick. This "sandwich" column is wrapped with tetrafluoroethylene (Teflon) tape to prevent the chemicals permeating through the sample from attacking the latex membrane surrounding the sample. Additionally, the tape and disk sides are smeared with high vacuum grease to control any small leaks. Next, a 0.025 inch (0.64 mm) thick latex membrane is unrolled over the sides of this column. Two 2.75 inch (7.00 cm) inside diameter o-rings are positioned over the membrane at each end, effectively squeezing the membrane into close contact with the greased disks. The combination of the high vacuum grease and the o-rings creates an effective seal between the disks and membrane to prevent permeant leakage.

The disk-sample-disk column is contained in the confining chamber. This chamber is made of 3/8 inch (0.95 cm) thick clear acrylic tube, with an inside diameter of 4.25 inches (10.8 cm) and two 3/4 inch (1.91 cm) thick aluminum endplates.

The aluminum base and cap disks, and thereby the sample, communicate to the outside of the confining chamber through 0.125 inch (0.32 cm) diameter nylon tubes and brass fittings that pass through the endplates. Two lines attach to each disk. One, which is attached to the top disk, introduces leachate to the sample; the second is provided to bleed off any air trapped in the disk or the top porous stone. It is closed by a valve during normal testing. One line to the bottom disk exits through the bottom endplate directly and carries off any permeant passing through the sample; the second line to the lower disk acts as a bleeder for the lower porous stone and disk. Both disks have a circular groove in their face to help disperse or collect fluid from a greater area of the porous stones. See Figure 3.

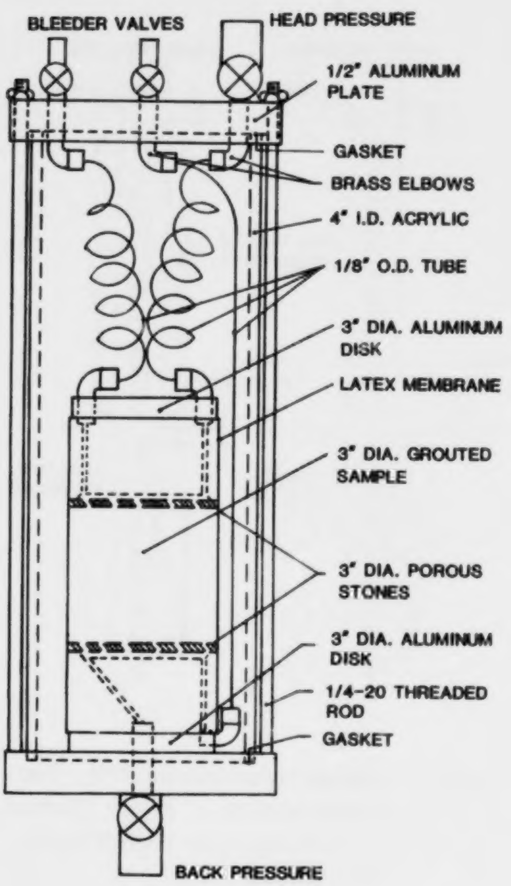

Figure 3. Permeameter.

It is believed that the above described triaxial type of encasement of permeability samples is the best for grouted soils. First, it provides a flexible and compliant boundary confinement to the flow of the permeant that will adjust to any surface irregularities in the sample. Second, it will also be flexible enough to adjust to any volume changes in the sample, either shrinkage or swelling.

It is hoped that the encasement using the tetrafluoroethylene tape and latex membrane combination will work for all chemical permeants. However, if leaks should develop, allowing the permeant to attack the membrane, molded fluoro-silicone jackets will have to be used for encasement.

Permeability Testing Apparatuses

Two permeability testing devices were designed to test the grouted soils. A constant head device is used in a special enclosure for possible carcinogenic or highly toxic permeants. A falling head apparatus is used for the less toxic permeants and the control liquid (distilled, deionized water). Both are pressure assisted systems.

The constant head device requires very little physical contact to read, adjust or maintain. It is preferred for the highly toxic permeants since it can be isolated in a vented glove box and only accessed for occasional adjustments. The falling head device yields more precise results and has built-in checks but requires more contact by the operator, making it potentially dangerous for use with carcinogenic or highly toxic permeants.

The constant head device accommodates twelve permeameters. The top of each of six permeameters is connected by a manifold to a pressurized permeant reservoir. Another manifold provides pressure to the confining liquid in the permeameters. Permeant passed through each sample is transported to a stoppered buret where the readings are made.

Two banks of six cylinders each are contained in a six foot long by three foot wide by four foot tall (1.83 m x 0.91 m x 1.22 m) clear acrylic glove box sealed under a vented metal hood (See Figure 4). All pertinent devices are also housed in this enclosure, including the gauges and pressure regulators, two permeant reservoirs, the manifolds, and burets. Readings on the burets are made through the transparent chamber. Adjustments to any valves and the filling of the reservoirs are accomplished using five sets of long neoprene gloves that are attached to evenly spaced portholes in the chamber walls. A small airtight door at each end allows for removal of equipment from the chamber. Air is constantly drawn through six flap valves located in the lower corners of the box and exhausted through the overhead hood. This keeps hazardous fumes to a minimum. All tubing and fittings are of resistant nylon and the valves are tetrafluoroethylene and brass.

The two typical versions of a falling

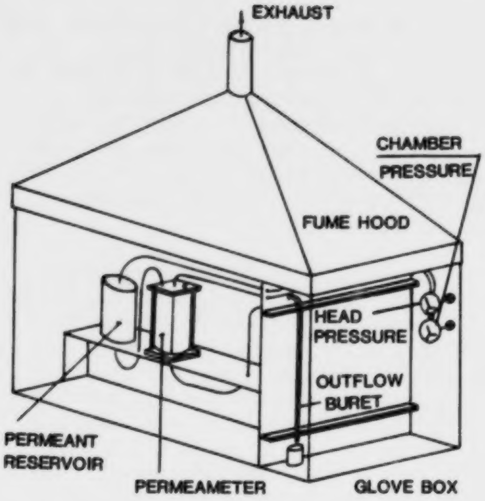

Figure 4. Constant Head Permeability Test Apparatus.

head permeameter station are shown in Figure 5. These are attached to a free-standing board. Each station supplies permeant through a standpipe to a sample in a permeameter. Any permeant that has passed through the sample is registered in a second standpipe. Agreement of the changes in the two standpipes affords a check for leaks in the permeameter or system. Provisions are made to assist the gravity head with pressure in both standpipes. Confining pressure is supplied by a manifold attached to a separate pressure regulator. A depleted standpipe can be filled from a supply line attached to a permeant reservoir on the board. Special, high volume standpipes are used for the more permeable samples. See Figure 5-b.

The falling head system is made up of 1/4 inch (0.64 cm) outside diameter Nylon tubing and Nylon fittings. Valves are brass with resistant, synthetic o-ring seals. Plug valves are used for all applications within the liquid filled portion of the network. These valves displace no liquid on closing and thereby do not change the levels in the sensitive standpipes.

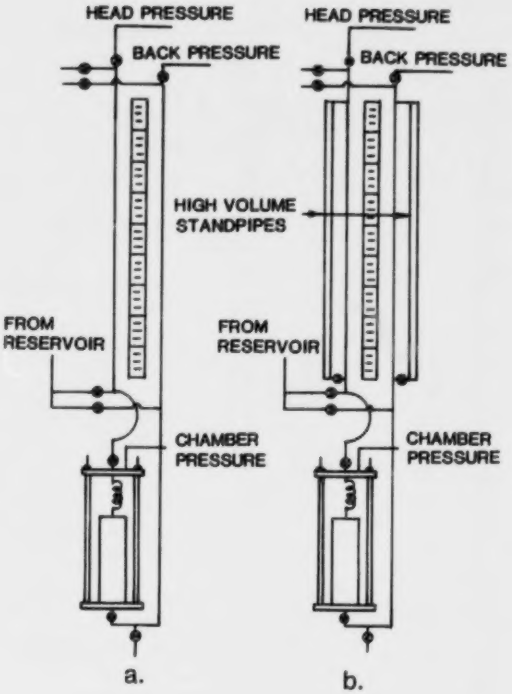

Figure 5. Falling Head Permeability Test Apparatuses: a. Basic Station; b. Variation with High Volume Standpipes.

The typical permeability test with toxic permeants is initiated by passing one-half of the sample's initial pore volume of distilled, deionized water through the sample. This is based on an estimate that after grouting the maximum volume of air and free water in a sample will not exceed one-half of the initial pore volume in the sand. The pressures required to produce this flow are adjusted according to the permeability and thickness of the sample, and by a limiting hydraulic gradient that is not high enough to cause erosion inside the sample. The flow must become steady by the time the one-half pore volume of distilled, deionized water has passed through the sample, as measured by the effluent volume. After this solution has been passed, the chosen toxic permeant is applied to the grouted soil sample under the same pressures. The rate of permeant flow through the grouted soil is measured at regular intervals and the permeability trends are observed.

As a minimum, a chamber pressure that is 10 psi (69 kPa) greater than the driving pressure is maintained to prevent any short circuiting of the permeant between the sample and the tetrafluoroethylene tape/membrane encasement.

Two test samples of each grout/permeant combination are tested simultaneously to check the uniformity of grouting and to check the test procedure for reproducibility. A third sample of the grout is simultaneously tested exclusively with the control liquid. All samples of a specific grout are prepared at the same time and under identical conditions to eliminate disparaties in the quality of samples.

RESULTS

The reactivity and corrosion tests on potential hardware materials resulted in a list of materials that were judged unaffected by xylene, methanol and acetone. These materials are Nylon 11, tetrafluoroethylene, dense polypropylene, aluminum (6061), stainless steel and brass. Materials to be allowed if not in contact with xylene, methanol or acetone are latex, neoprene and acrylic.

The durability test on the grouted soil samples gave varied results. In the methanol bath, urethane samples lost an average of 12% of their weight and softened to the point of making handling without tearing the sample difficult. Urethane also softened in the water but gained an average of 15% by weight. No visible degradation of these samples were noted.

Urethane samples in the xylene had no noted weight change, but were noticeably harder after immersion. The normally smooth faces of the specimens showed some etching between sand particles. The sodium silicate samples had no notable degradation, yet lost an average of 7.5% of their weight in methanol, 3.5% in acetone and gained 3% of their weight in xylene. A 1% weight decrease was noted in water.

The procedures that were developed for grouting the soil samples, using three different grouts, have proven to be excellent. By using the developed deairing method, the samples proved to be very uniform in their properties and are easily reproduced. The grouting mold works well, it is easy to use; and it allows close control of the dimensions of the samples. Although the AV-100 grout gave the lowest permeability values among the grouts used, and its use resulted in the most consistent samples, because of its toxicity it will be replaced in future work by its acrylate counterpart, the AC-400 grout.

The triaxial permeameter that was developed is simple, compact, inexpensive and works well. The rigid mold type permeameter was tried but was abandoned because of separation between the mold and the shrinking sample and a consequent short-circuiting of permeant flow. Also, it could effect permeability results if the grouted sample would have a tendency to swell as a reaction to the permeant.

A permeability sample diameter of three inches was chosen as a convenient dimension as it is close to the usual triaxial sample size of 2.8 inches (7.1 cm). The thickness of the samples is varied between one and three inches, depending on the permeability of the grouted soils, using the smaller thickness for samples with the least coefficient of permeability.

The developed methods of wrapping and encasing the samples is working well. It effectively confines the flow of permeants to within the samples.

The confining pressures chosen in prototype testing are to simulate typical overburden pressures in-situ, but should be at least 10 psi higher than the head pressures to ensure a good seal between the samples and their membranes.

The falling-head permeability test apparatus works very well. It is accurate, straightforward to operate, and is durable. It is the preferred type of device if the permeant used is non-toxic or only mildly toxic, and adequate protection against injuries can be provided by goggles and protective clothing.

The tests in progress use elevated driving pressures for accelerated testing. However, it was found that even the control liquid can break through a sample if the hydraulic gradient is too high. This critical hydraulic gradient seems to depend on the type of grout and the permeant used. To avoid a breakthrough with the control liquid, each type of grouted sample must carefully be pretested with gradually increasing hydraulic gradients and by closely monitoring the flow rates. The flow rate of the control liquid must remain constant indefinitely at the selected driving pressures.

The best procedure for permeability testing seems to be to first establish the desired driving pressures, as explained above. Then three identical grouted samples are subjected to permeability testing with the control liquid as the permeant. One-half of a pore volume of this liquid is passed through the samples. After that, the hazardous leachate is introduced as a permeant for two of the samples while the third sample continues to receive the control liquid. During the tests, the flow rates are continuously monitored and the permeability values are calculated and plotted against the flow volumes to observe developing trends.

At the time of this writing (September, 1983), as part of the shake-down of the equipment, permeability tests are being conducted on twelve grouted samples. They are being tested in the falling-head permeability device. Four of each of the acrylamide, the urethane and the sodium silicate grouted samples are being tested. They are all three inches in diameter. The thickness of the sodium silicate samples is three inches, while that of the acrylamide and urethane samples is one inch.

Permeability tests with the control water over a two week period, and with a minimum total flow equaling one pore volume, resulted in stabilized flows at the following average values of permeability: 4 x 10^{-10} cm/sec for acrylamide samples, 1.4 x 10^{-8} cm/sec for urethane samples and 1.0 x 10^{-5} cm/sec for sodium silicate samples. The sodium silicate samples were grouted without the carbon dioxide purge method and are considered of inferior quality. Improved sodium silicate samples will be prepared for further testing.

After the two week period mentioned above, reagent grade acetone was introduced into two acrylamide and two urethane samples. In the following two weeks, the permeability of the urethane samples decreased by approximately 6 fold. The permeability of the acrylamide samples first decreased slightly, then began to increase slowly, and they both failed by breaking through shortly thereafter (See Figure 6).

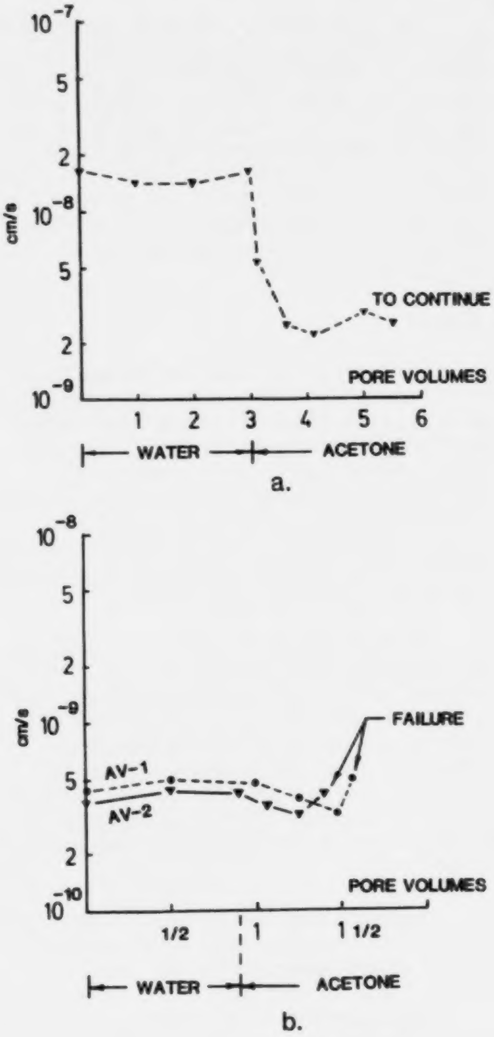

Figure 6. Permeability Test Results: a. Silica Sand with Urethane Grout; b. Silica Sand with Acrylamide Grout.

Immediate future research will systematically test the resistance to percolation of sodium silicate, urethane, cement-bentonite and acrylate grouts, subjected to reagent grade acetone, glycol, methanol and xylene permeants.

ACKNOWLEDGEMENTS

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PRODUCTION, MIGRATION, AND HAZARDS ASSOCIATED WITH TOXIC AND FLAMMABLE GASES AT UNCONTROLLED HAZARDOUS WASTE SITES

Riley N. Kinman, David L. Nutini
RNK Environmental, Inc.
Covington, Ky. 41017

ABSTRACT

The extent of production, migration, and hazards associated with toxic and flammable gases at uncontrolled hazardous waste sites was determined by literature review. Emphasis was placed on volatilization and migration of gases (other than methane); short- and long-term gas problems encountered before and during remedial action and how these are coped with; costs associated with gas control; chemical group compatibility; and the most frequently reported toxic and flammable gases occurring at uncontrolled hazardous waste sites. Based on the review, gas migration problems are site specific and are manageable; concentrations in air have been measured in the low mg/l to µg/l range for most gases reported; and costs of gas migration controls are expensive. Costs ranged from $17,300 to $273,510.

INTRODUCTION

Superfund legislation requires that cleanup of hazardous materials be accomplished at many remedial action sites. In the cleanup effort, there is the possibility that toxic and flammable gases will be released to the environment, both from natural and man-made activities. This study determined the extent of production, migration, and hazards associated with both toxic and flammable gases at hazardous waste sites, including surface impoundments, landfills, drum storage areas and contaminated soil, where remedial action is either underway, contemplated or finished.

VOLATILIZATION AND MIGRATION

Volatilization, mainly from the more toxic of the halogenated organics and aromatic hydrocarbons, is the primary process where waste containing these organics at uncontrolled hazardous waste sites are converted from a liquid or solid state to a gaseous or vapor state. A number of factors influence volatilization including the physical-chemical properties of the substance such as vapor pressure, temperature (boiling point and flash point), molecular weight, solubility, and environmental factors such as air-surface diffusion rates, wind speed, absorption/adsorption, air temperature and pressure. For example, a substance with a high vapor pressure, a low molecular weight, a low boiling point, and a low solubility typically has a high volatility.

Increasing wind speed, creating increased turbulence,also increase rates of volatilization from surface impoundments. Thibodeaux et al, 1982 (1) found that natural gas transfer coefficients measured for methanol in surface impoundments averaged 2,680 cm/hr, while the turbulent gas transfer coefficients averaged 13,900 cm/hr. Wind may also have a reverse effect favoring a decrease in the gas concentration in air by dilution. This depends on the location of the receptor.

Rising air temperatures increase volatilization as demonstrated by Shen and Tofflemire, 1980 (2), where concentration ranges of PCBs in the summer were 246-300 $\mu g/m^3$ and only 0.05-3.0 $\mu g/m^3$ in the winter.

Absorption/adsorption of a liquid organic chemical onto a solid adsorbent or soil affects volatilization. Shen and Tofflemire, 1980 (2), showed that the rate of volatilization of Aroclor 1242 was less for organic topsoil than for coarse sand. The coarse sand had more surface area to adsorb, and thus, desorb the chemical than did the topsoil which was denser and had less porosity. This is also an important factor when considering diffusion through the soil as part of the chemical migration process (discussed below).

Since many combinations of wastes and conditions may occur at uncontrolled hazardous waste sites, other factors influence volatilization. The solid and/or liquid waste types, waste concentration, soil permeability, moisture content, gas pressure, all contribute to diffusion of volatile substances from waste sites. For example, increase in the soil moisture content, decrease in the soil permeability, and compaction of the soil cover will decrease the diffusion rate of organic chemicals.

Another pathway of migration for organic compounds in air besides volatilization (diffusion) involves the adsorption/absorption of these chemicals onto fine particles (particulate matter, soil dust, coal fines). Natural and artificial activities like wind erosion and excavation may create localized or long-range air pollution problems.

Movement of leachate and/or groundwater containing organic compounds is another migration pathway. The contaminants carried in the leachate/groundwater volatilize into the air creating odor and health problems. This may occur onsite as well as off-site depending on the extent of movement.

PROBLEMS BEFORE AND DURING REMEDIAL ACTION

The most typical types of problems discovered before remedial action at uncontrolled hazardous waste sites indicating a need for such action include odors, vegetative damage, human and animal health effects, fires and explosions, discoloration of soil, and deterioration of metal surfaces. A comprehensive list of the types of toxic and flammable gases measured where these problems were noted are given in Table 1.

The most typical types of problems encountered during remedial action include odors from leaking drums, odors from penetrating or opening drums while sampling, or odors emitted in excavating or drilling the site; meteorological conditions (high temperatures and fog) which increased volatilization or caused organic vapor buildup; and topographical conditions (valley setting) which prohibited sufficient ventilation of the site; heat stress due to wearing protective clothing to prevent exposure to gases; community stress from seeing on-site workers wearing protective gear while they may have no such protection; other human health effects due to chemical exposure; fires and explosions; fugitive dust emissions; anaesthetic effect by odorless chemicals. The types of toxic and flammable gases measured where these problems were found are also included in Table 1.

TABLE 1. TOXIC AND FLAMMABLE GASES MEASURED AT REMEDIAL ACTION SITES

Types		
Toluene	Chlorotoluene	Trans-1,2-Dichloroethene
Benzene	Tetrachloroethane	Hexachlorobenzene
Phenols	Chlorobenzene	1,1-Trichloroethane
Ethylbenzene	Xylenes	Dichloromethane
Naphthalene	Trichloroethane	Tetrachloromethane
Vinyl Chloride	Chloroform	Methylbenzene
Methylene Chloride	Tetrachloroethene	Dimethylbenzene
Chloroethane	Vinylidene Chloride	Trimethylbenzene
Trichloroethylene	1,2-Dichloroethane	Dichlorobenzene
Pesticides	Hydrogen Sulfide	Trichlorobenzene
Coal Tar Residues	Acetone	Carbon Tetrachloride
Methane	Hexane	

SHORT- AND LONG_TERM PROBLEMS ASSOCIATED WITH SITE RESTORATION TO MITIGATE GAS GENERATION OR MIGRATION

Several short-term problems raised or encountered in the part by site investigators include: attempts to measure or estimate gases are complicated by the wide range of contaminants and interference posed by other gas sources; scarcity of published gas monitoring data on rate and amount of gas production; and variability in meteorological conditions affecting gas generation and migration rates. These problems are now overcome by gathering background data from Federal, State, and Local officials, manufacturers, and others who live or work near the site or by performing field investigations using environmental air monitoring equipment (Table 2).

Long-term contamination effects from toxic and flammable gases are not yet well known. However, it is believed that long-term airborne effects from predicted concentrations of organic vapors could cause increased cancer risks. Also many short-term accumulations of substances could lead to long-term problems. The risks from eventual long-term accumulations can be decreased or abated with sufficient controls.

CONTROLLING PROBLEMS AT UNCONTROLLED HAZARDOUS WASTE SITES

To properly respond to a gas problem at an uncontrolled hazardous waste site, many considerations are made during the site investigation, mitigation, and closure. Usually a preliminary assessment of the site is made before any comprehensive plan of action is taken. This is done in order to obtain data to identify hazards or gaps in known information in order to plan further investigations or the safe response to site cleanup.

Another procedure used is air monitoring or, in the absence of data, air modelling. This may be used before, during and after response to a site and may be used on-site as well as off-site. Several types of air monitoring equipment used to monitor specific hazards are given in Table 2.

Once the need for remedial action is established, a comprehensive site plan called a Remedial Action Master Plan (RAMP), integrating health and safety procedures, is initiated. The complete plan is outlined in the final paper which includes such items as a base of operations, personnel, a decontamination station, coordination of activities with all officials,

TABLE 2. TYPES OF EQUIPMENT USED IN AIR MONITORING FOR SPECIFIC HAZARDOUS SUBSTANCES

Hazard	Equipment
Explosive Atmosphere	-combustible gas indicator
Oxygen-deficient Atm.	-oxygen meter
Toxic Atmosphere	-organic vapor analyzer (OVA-GC) -photoionization detector (PID) -flame ionization detector (FID) with gas chromatograph (GC) option -colorimetric tubes -collection systems using sampling pumps in conjunction with absorption tubes, detector tubes, filters, and impingers. After collection, lab analysis would include use of gas chromotograph/mass spectrophotometer (GC/MS), GC/Electron Capture, Atomic Absorption (AA), or wet chemistry methods.
Radioactivity	-radiation survey meters (alpha, beta, gamma) -passive monitors (alarms) -dosimeters (film badges)

examination of site characteristics, levels of protection (clothing and safety equipment), medical surveillance, proper equipment for safe clean-up, methods of controls, odor surveys, safe handling and sampling procedures, and emergency plans.

Methods of control may be natural or artificial. The various methods presently used include: natural dilution and dispersion into the atmosphere; natural soil barriers; gas treatment systems; covers; foams; predisposal treatment; pipe and trench vents; impermeable barriers; and gas collection systems. Because every site is unique, use of these controls is quite variable. Some controls are used in combination with one another to prevent migration, for detoxifying substances, or to protect structures. For example, the best protection scheme (Figure 1) for protecting an existing structure might include a permeable trench system, complete with gas extraction wells, header system, and exhaust fan-induced gas exhaust.

COSTS ASSOCIATED WITH GAS CONTROL

References report costs for several gas migration control techniques. All sample costs were based on hypothetical sites and were obtained from published guides and other literature sources. Costs of specific gas migration control techniques according to Paige et al, 1980 (3), including system details are given in Table 3.

The range (using the U.S. high and low average) of life cycle costs including initial capital and first year operation and maintenance, for gas migration control techniques according to Lippitt et al, 1982 (4), are given in Table 4.

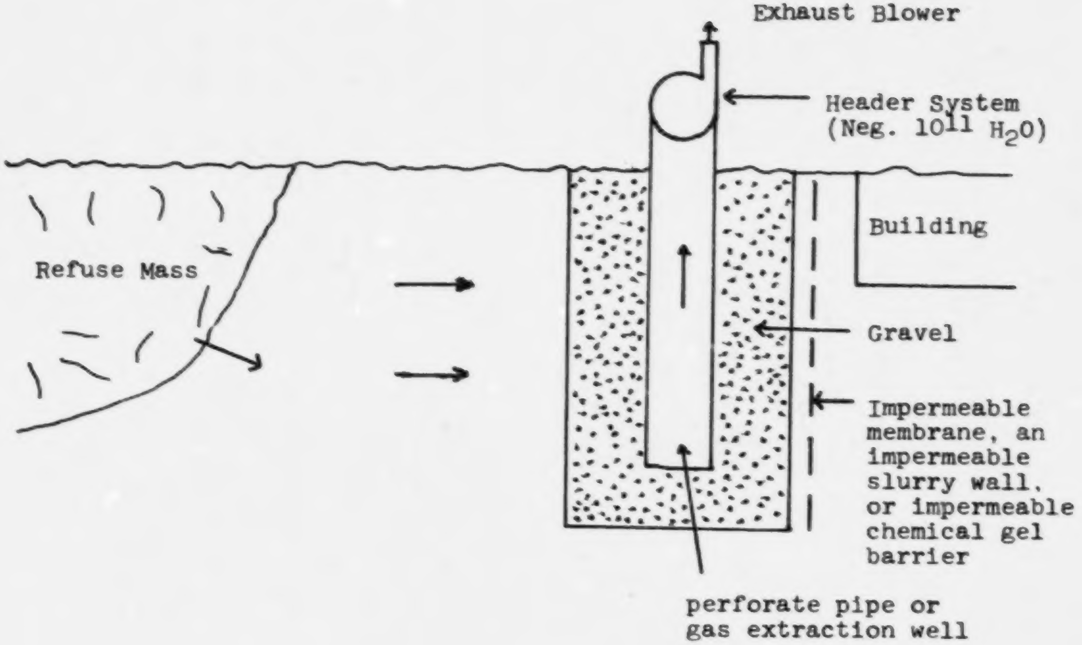
Exhaust Blower
Header System (Neg. 10ll H_2O)
Building
Refuse Mass
Gravel
Impermeable membrane, an impermeable slurry wall, or impermeable chemical gel barrier
perforate pipe or gas extraction well

FIGURE 1. Permeable trench system with induced draft and header system.

TABLE 3. COST OF SPECIFIC GAS MIGRATION CONTROL TECHNIQUES (3)

Technique	Details	Total Cost
Trench Vents	As constructed; dimensions are 20' deep, 4' wide, 500' long. Cost covers excavation, spreading of backfill material, well point dewatering, sheet piling, laterals, risers. Cost of treatment of water withdrawn during dewatering is not included.	$273,510
Pipe Vents	For a single forced ventilation pipe vent 4" in diameter and 30' deep. Includes cost for installation of well, PVC casing, mushroom top, elbow piping, and a small fan applicable to one vent.	$1,110
Gas Collection System	This consists of a surface gas collection network connected to the heads of 4 pipe vents. The distance between each vent is 200' and an additional 20' of PVC pipe is needed to connect the last vent to the fan. Pipes are designed to maintain the required head throughout the system. Also, PVC elbows, PVC tees, butterfly valves and flowmeters are used as needed. Cost includes installation and materials.	$14,230

TABLE 4. RANGE OF COSTS OF SPECIFIC GAS MIGRATION CONTROL TECHNIQUES- CONSTANT UNITS*(4)

Technique	Range of Life Cycle Cost
Passive Vents	$17,300-25,220
Passive Trench Barriers	$29,015-44,180
Active Gas Extraction Wells	$28,900-48,200
Surface Seal with Clay	$96,300-163,300
Surface Seal with Asphalt	$67,300-92,700
Surface Seal with Fly Ash	$95,900-165,700

* All units in dollars per hectare of site surface area.
ha = 0.41 acres

CHEMICAL GROUP COMPATIBILITY

Table 5 represents one of thirty-eight chemical groups and the chemical groups with which it is reactive. Mixture of these chemical groups will result in a gas emission or gas-related incident such as a fire (F), an explosion (E), heat generation (H), Toxic gas generation (GT), or flammable gas generation (GF) (5). This type of information serves as a good indicator list of combinations that should be avoided when working a site or that could be used in determining potential gas problems when assessing a site.

TABLE 5. CHEMICAL GROUP COMPATIBILITY (5)

Reactive Group	with	Results
Acids, Organic	-cyanides	GT, GF
	-dithiocarbamates	H, GT, GF
	-fluorides, inorganic	GT
	-metals, alkali & alkaline earth, elemental	GF, H, F
	-metals, other elemental & alloys as powders, vapors, or sponges	GF
	-nitrides	H, GF
	-sulfides, inorganic	GT
	-explosives	H, E
	-oxidizing agents, strong	H, GT
	-reducing agents, strong	H, GF

FREQUENTLY REPORTED TOXIC AND FLAMMABLE GASES OCCURRING AT UNCONTROLLED HAZARDOUS WASTE SITES

Twenty-one of the most common chemicals found at uncontrolled waste sites that have resulted in toxic and flammable gas problems are cited in the final report. The final report not only lists these chemicals but gives information as to their molecular weight (MW), boiling point (BP), vapor pressure (VP), flash point (FP), solubility (Sol), Provisional Limits in Air (PLA), Threshold Limit Values (TLV), Short-term Exposure Limits (STEL), distinct odor (DO), Threshold Odor Concentration (TOC), odor characteristics, volatility, health effects, protection level, and measured concentration ranges found in air at vaious sites around the U.S., Great Britain, and Germany. A sample of this information is given in Table 6 for benzene.

ACKNOWLEDGEMENTS

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TABLE 6. INFORMATION ON BENZENE

Type	MW	BP (°F)	VP (mm Hg at 20°C)	FP (°F)	Sol (mg/l at 20°C)	PLA (mg/m^3)	TLV (mg/m^3)	STEL (mg/m^3)	DO (mg/m^3)	TOC (mg/m^3)	Odor Charac.
Benzene (Benzol, Cyclohexatriene)	78.1	80.1	76	12 (TCC)	1780	0.8	80	75	310	1-180	Strongly odorous; sweet; aromatic

Volatility	Health Effects	Protection Level	Conc. Ranges	Site	Reference
-Volatile	-Irritation of eyes, nose and respiratory system; headache, nausea, anoremia, fatigue; dermatitis, bone marrow changes, blood abnormalities; carcinogenic; regarded as a cumulative poison due to the slow buildup in the body tissues and fluids because of its low solubility in the circulating blood.	B	522.7 µg/m^3	Love Canal	26
			10-2000 ppm	BKK[b]	18
			3.0-4.8 ppb	BKK[c]	18
			270 µg/m^3	Love Canal	1
			2066 ppm	Ohio River	28
			19.2 ppb	Chem-dyne	11
			T-29.2 ppm	Lees Lane	85
			0.2-5.4 ppm	---------[a]	67
			<0.03-3.56 ppb	Midco I	35
			0.3-10 mg/m^3	Unidentified	81

TCC = Tagged Closed Cup
Protection Level B = Self-contained breathing apparatus and protective clothing (allows some exposure to neck, back of head, and some parts of body)
a = represents 9 landfills
b = in landfill gas
c = in ambient air around site
T = Trace

MIGRATION OF INDUSTRIAL CHEMICALS AND SOIL-WASTE INTERACTIONS AT WILSONVILLE, ILLINOIS

R. A. Griffin, R. E. Hughes, L. R. Follmer, C. J. Stohr, W. J. Morse, T. M. Johnson,
J. K. Bartz, J. D. Steele, K. Cartwright, M. M. Killey, and P. B. DuMontelle

Illinois State Geological Survey
615 East Peabody Drive
Champaign, Illinois 61820

ABSTRACT

Clay soil behavior and migration of industrial chemicals are being investigated at a hazardous-waste disposal facility in Wilsonville, Illinois (Macoupin County). The study was initiated after the Illinois Supreme Court affirmed a trial court order requiring the wastes at this site to be exhumed and removed. The May 1981 order provided a unique opportunity to examine in detail the effects of the wastes on soils below and adjacent to the site and to measure the migration of contaminants from the trenches. Work is currently in progress; however, preliminary results have been obtained which permit a detailed geologic description of the site and a preliminary evaluation of hydrogeologic conditions relative to contaminant migration, clay-organic chemical interactions, and the susceptibility of the cover material to collapse as a result of subsurface erosion (piping).

INTRODUCTION

As an outgrowth of a 1982 Illinois Supreme Court affirmation of a trial court order requiring the exhumation and removal of hazardous wastes buried at a disposal facility near Wilsonville, Illinois (Macoupin County) the Illinois State Geological Survey supported by the U. S. Environmental Protection Agency, the Illinois Environmental Protection Agency, and the site owner, SCA Services, Inc., began a study to determine the cause or causes of contaminant migration at the facility. The background events, overall site characteristics and project description have been given previously (Griffin et al., 1983; Johnson et al., 1983; and Stohr, 1983).

Routine monitoring of the Wilsonville site by the Illinois Environmental Protection Agency revealed that organic contaminants were migrating 100 to 1000 times faster than predicted. Two obvious questions were posed: (1) Why were these organic compounds migrating faster than predicted, and (2) what are the implications to land disposal of similar wastes at other sites? The court order to exhume the wastes provided a unique opportunity for a project to examine in detail the natural soil conditions and the effects of the wastes on the soil materials below and adjacent to the site and to measure the migration of contaminants from the trenches.

Development of Cracks due to Syneresis

Cracks in geologic materials may result from different processes such as desiccation, freeze-thaw, tectonic activity, subsidence of mined-out or karst areas, and syneresis. Syneresis is a chemical reaction which causes shrinkage and dewatering of a colloidal material due to aggregation of particles by physico-chemical attraction. Syneresis cracks form as the material shrinks. The associated cracks are common in nature and are observed as open cracks, mineral fillings, slicken-sides, and "joints" in rocks and soil materials and should not be confused with desiccation stress-relief, or other cracks, which are very similar (White, 1964). The extent to which syneresis cracks can affect liquid migration through a clay-rich material was illustrated by Kallstenius (1963). He found syneresis cracks 6-10 meters below ground surface in a glacial clay; the cracks were large enough and extensive enough to provide the sole water supply for a town of 7,000 people.

Failure of landfills to prevent escape of hazardous wastes may result from several natural and man-induced conditions. Contaminated aqueous wastes and organic solvents can move along pre-existing cracks, joints, root traces, wells, or mine shafts. Evaluation of potential landfill sites often overlooks the existing natural cracks and fractures. Also, potential clay-contaminant interactions affecting the physical structure of soil materials are usually ignored.

Interactions between clay, percolating water, and contaminants can result in high rates of contaminant migration. Flocculation increases the ease of liquid migration through a clay-containing material. Minerals that expand in water can undergo relative expansion or collapse caused by (1) replacement of water by other solvents, (2) cation exchange, or (3) increasing ionic strength at the clay-solvent interface. If relative collapse of the clay structure occurs, the result will be syneresis cracks causing the material to have much higher permeabilities. Expansion of the clay structure can disrupt clay liners and will often be followed, after a change in pore chemistry, by relative collapse of the clay mineral structure and resultant higher permeabilities.

Anderson, Brown, and Green (1982) found much higher permeabilities for soils exposed to various organic solvents. They thought this could be caused by the increased flocculation of clay particles and by collapse of expandable clay minerals such as smectite. Murray and Quirk (1982) have shown that dry, pressed pellets of nonexpanding clays will expand when solvated by various solvents in direct proportion to the dielectric constant of the solvent. It seems possible that clay materials exposed to water, which has a relatively high dielectric constant, would shrink when exposed to organics with a lower constant. This supports the mechanism for producing higher hydraulic conductivities suggested above by Anderson et al. (1982).

The failure of clay barriers in some instances to contain leachate from landfills or impoundments may result from several natural and man-induced causes. All of the causes of flocculation and/or interlayer collapse already mentioned may cause syneresis cracks to form. The extent to which syneresis cracks can affect leachate migration and the question of synergism between large numbers of natural and artificial conditions (agents) are essentially unstudied.

PURPOSE, OBJECTIVES, AND APPROACH

The project aims are (1) to determine why organic contaminants detected in monitoring wells around the trenches have migrated faster than predicted, but perhaps more importantly, (2) to provide insight into many other questions regarding the efficacy of land disposal of hazardous wastes, particularly organic liquids. The scope of work includes studies of several aspects of the behavior of soil materials at the site as follows:

Site Characterization

1. A detailed geologic description.

2. Comparison of field- and laboratory-measured values of hydraulic conductivity.

3. The relative significance of secondary hydraulic conductivity or fracture flow.

4. The effective porosity and its relative impact.

Organic Chemical Effects

1. Measurements are being made of migration rates of organic chemicals through the soil materials at the site.

2. Studies will be made to determine the effects of certain organic chemicals on permeability.

3. Studies are being carried out on the effects of organic chemicals on pore structure and volume.

4. A screening test is being developed to determine the effects of leachate and organic chemicals on clay structure and permeability.

Liquid Level and Acid Drainage

The hydrogeology and water balance of the trenches are being examined to determine the effects of hydraulic head under natural conditions and from the adjacent pile of coal cleaning refuse preparation (gob) on the bottom and side wall permeability. The strong acidity and high inorganic salt content of leachate from the gob pile are also being examined with regard to impact on trench conditions (i.e. hydraulic conductivity and accelerated corrosion of drums).

Condition of Trench Covers and Subsidence

Detailed maps of the trench covers are being prepared showing major failures of the covers and the extent of these features. The condition of the covers is also being examined as the trench materials are removed to determine the role of surface and subsurface erosion on the failures of the trench covers and on the water balance within the trenches. Monuments established at the site are surveyed with precision instruments at regular intervals to determine slight changes in elevation. Failure of the abandoned coal mine 300 ft below the site would be indicated if parts of the site show specific patterns of subsidence.

Condition of Drums and Wastes

The condition of the drums and other wastes is being documented periodically as they are removed from the trenches to help determine the effects of the leachate on the drums and earth materials, the relative leachate strength, and drum life expectancy.

RESULTS

This paper describes work currently in progress. As such the results presented should be considered as tentative and subject to possible reinterpretation.

Geology of the Site

The thickness of the glacial deposits, collectively referred to as drift, ranges from about 50 to 100 feet. A silty to clayey Pennsylvanian shale occurs immediately beneath the glacial deposits at the site. A site map showing the location of drill holes with respect to the trench and gob pile and the location of the cross section is given in Figure 1. The sequence of nonlithified (or glacial) materials underlying the site is illustrated in Figure 2, a cross section of the site, and in the generalized stratigraphic column in Figure 3. Approximately the lower half of the sequence is composed mainly of fine grained, silty to clayey till of the Banner Formation. Several till units have been recognized on the basis of clay mineralogy, morphology, and truncated soil profiles within the Banner. The uppermost till at Wilsonville is the Vandalia Till Member of the Glasford Formation. It ranges in thickness from about 25 to more than 60 feet. It rests upon the Banner Formation and comes to within about 3 to 5 feet of the ground surface on the site. Near the site the Vandalia outcrops along side slopes of valleys of dissecting streams. The Vandalia is commonly divisible into 4 zones from the top down: 1) weathered, leached, clayey, stiff ablation till (the Bt of the Sangamon Soil); 2) weathered, leached, loamy, soft "mushy" ablation till; 3) partly weathered, calcareous, loamy, brittle, fractured, dense, basal till; and 4) unweathered calcareous, loamy, stiff, semiplastic, dense basal till.

Several variations from this general scheme have been observed in the Wilsonville cores studied thus far. In a few places the upper part of zone 3 is calcareous and soft with a high water content. The unweathered zone 4 is sandy in its

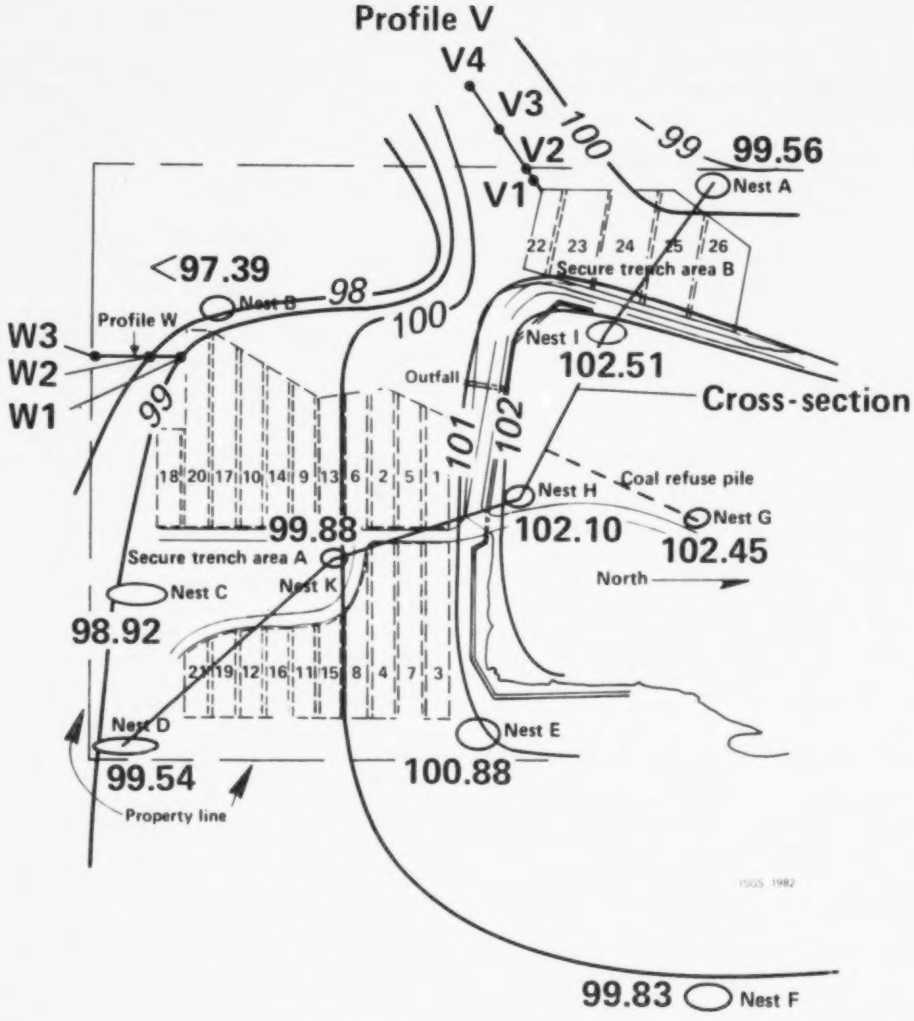


Figure 1. Site map showing: potentiometric surface of lower ablation till, April 1983; locations of trenches in relation to well nests, profiles, and cross sections; and elevations (meters) based on arbitrary datum point.

upper part but contains some silt rich zones in the lower part. The sandy phase till is stiffer and less plastic than the silty phase. The phase relations between subunits appear to be caused by glacial deformation, shearing and stacking. Silt; sand- or gravel-rich lenses, partings or layers, are few to common in most cores. They are most often less than 2 in thick, but range up to 2.5 ft thick in one boring (V4D) for an interval of sand and gravel. So far no evidence for continuity of sand has been substantiated for lateral distances beyond a few meters.

The upper part of zone 3 is highly jointed in places, and the amount of jointing dissipates with depth. Most joints are horizontal, as many as two per in; fewer are oblique to vertical, about 1 to 5 per core. Joints are stained with iron or other compounds. The major factors in joint development are related to stress release, desiccation, increased brittleness caused by oxidation and a slight carbonate cementation.

During exposure of the Vandalia Till to weathering, the Sangamon Soil developed. The Sangamon Soil formed directly in the ablation phase of the Vandalia Till. This interval of weathering caused a high degree of mineral alteration and the development of the clay enriched zone 1.

The surficial materials covering the Vandalia Till at the site are principally wind-blown silt deposits. Overlying the Vandalia Till is the Roxana Silt that was deposited mostly during the interval from about 30,000 to 45,000 years ago. The upper 2 to 5 feet is the Peoria Loess, which was deposited about 12,000 to 25,000 years ago. Weathering of these silty deposits has changed the texture to a silty clay loam (30 to 40% clay) in most places. The surface soil horizons are less clayey, generally with 15 to 25% clay. The Roxana often contains 20 to 30% clay. The modern soil at most places has reached a mature state in terms of strong horizonation and chemical leaching. The natural pH ranges from 4.3 to 5.5 and most weatherable minerals have been altered. Areas adjacent to the trenches are covered by 1 to 3 feet of backfill soil material. A flattened coal refuse pile preparation (gob) covers about 10 acres of the site with about 15 to 40 feet of rock debris from an underground coal mine.

Special emphasis has been placed on assessing the normal pedologic and geologic features in and around the trenches to develop a classification for materials that distinguishes classes of normal and disturbed materials. Cores from and backhoe pits in the surrounding area have also been examined and evaluated to substantiate the stratigraphic interpretations presented.

HYDROGEOLOGIC/GEOCHEMICAL STUDIES

Hydrogeologic and geochemical investigations of the site are being conducted and include: (1) borings of 18 piezometer/monitoring well nests (nests A to K, profiles V and W in Figure 1), (2) three to nine piezometers and monitoring wells per nest, and (3) 45° angle piezometers at nests A, B, E, and K to attempt to measure the influence of vertical fractures on hydraulic conductivity. The details of the design, construction, and experimental plan are given in Griffin et al. (1983) and in Johnson et al. (1983), with the exception of angle piezometers. The angle holes were drilled on a 45° angle and the cased interval was backfilled by pumping grout from the bottom of the casing to the ground surface rather than the intervals of expanding concrete and bentonite described by Griffin et al. (1983) and Johnson et al. (1983). All other design and construction details were identical to those described for the vertical piezometers.

Piezometers are being used initially for in-situ hydraulic conductivity tests. After the water levels stabilize, piezometers are used to establish the long-term potentiometric surface and in turn the hydraulic gradient and flow across the site. The elevation of the potentiometric surface at the site measured in the piezometers in April, 1983 is shown in Figure 1, and in the cross section, Figure 2. The effect of the coal refuse pile on shallow groundwater flow pattern is evident. A groundwater mound is present beneath the coal refuse pile resulting in shallow groundwater flow toward secure trench area B to the west and secure trench area A to the south. Some disposal trenches in each area were apparently excavated below the water table; however, the trenches may have remained relatively dry during the disposal operation due to the very low hydraulic conductivity of the surrounding till. The presence of the ground water mound beneath the coal refuse

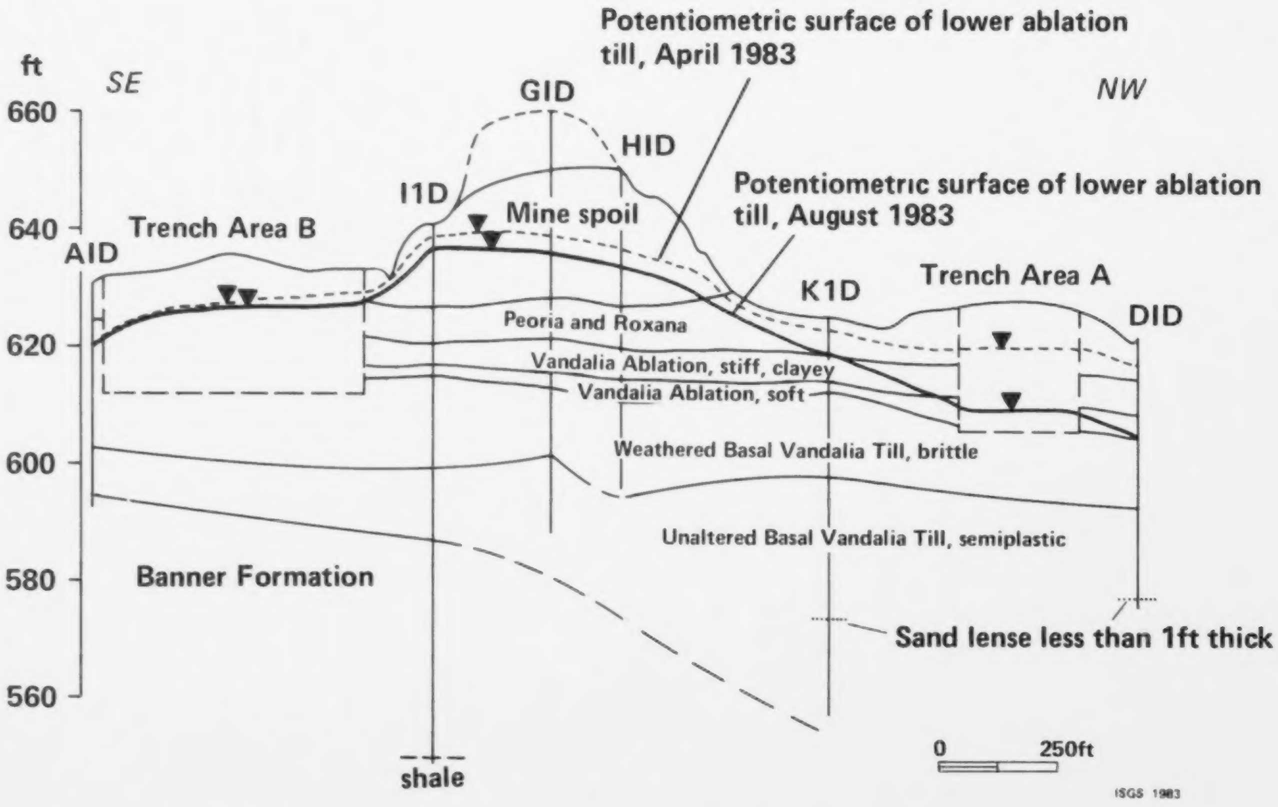

Potentiometric surface of lower ablation till, April 1983
ft
SE
NW
660
640
620
600
580
560
GID
HID
I1D
Potentiometric surface of lower ablation till, August 1983
Mine spoil
AID
Trench Area B
K1D
Trench Area A
DID
Peoria and Roxana
Vandalia Ablation, stiff, clayey
Vandalia Ablation, soft
Weathered Basal Vandalia Till, brittle
Unaltered Basal Vandalia Till, semiplastic
Banner Formation
Sand lense less than 1ft thick
0
250ft
shale
ISGS 1983

Figure 2. Geologic cross section of the site with potentiometric surface of Lower Vandalia Ablation zone.

pile is also significant because of the potential effects of acidic, highly mineralized, coal refuse leachate on the geologic materials, wastes, and drums at the disposal site. The pH of the coal refuse leachate varied between 1.85 and 2.40; whereas soil beneath the refuse at Nest I varied between a pH of 1.95 at the soil-gob interface to a value of 3.75 at 4.25 ft below the refuse. The effects of the acid leachates were not apparent at depths greater than about 5 ft where soil pH and EC values returned to the normal range. It is tentatively concluded that the high buffering capacity of the soils have mitigated any potential influence of the acidic refuse leachate on wastes or containers within the trenches. The major influence of the gob pile at this time appears to be its strong effect on the local water table and ground water flow directions.

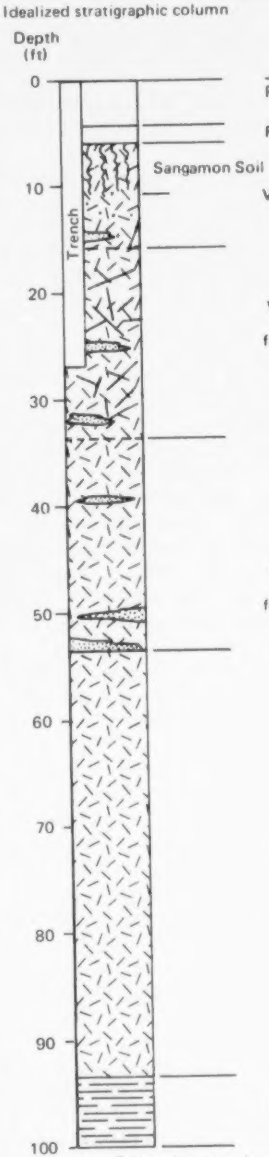
Preliminary results of the in-situ, field tests of hydraulic conductivity calculated using the methods of Cooper et al. (1967) and Papadopulos et al. (1973) are compared to the results of reported laboratory tests of hydraulic conductivity of similar materials in Figure 3. The hydraulic conductivity of the Vandalia Till determined by laboratory tests of recompacted samples is very low, especially for reportedly unfractured basal till. Laboratory-derived values for samples of Vandalia Till were all reported to be 2.0 x 10^{-7} cm/sec or less (SCA, 1982). The hydraulic conductivity calculated from field injection (slug) tests, including a limited number of angle hole results is however, generally significantly greater than that calculated from laboratory tests for the same apparent material. Field measurements of the hydraulic conductivity of intervals of ablation till and fractured basal till, however, were found to be similar for both vertical and angle holes and as much as three orders of magnitude greater than laboratory measured values. In the ablation till, this may be due to very thin sand seams or small interconnected fractures within the relatively soft till. The locally, highly-fractured nature of the upper portion of the more dense basal till probably results in much greater hydraulic conductivity values than those observed in recompacted samples of the same material.

The results of field tests of hydraulic conductivity of the relatively unfractured basal till are significantly lower than the overlying till zones; however, they are still much greater than the results of corresponding laboratory tests. The reasons are not clear for this discrepancy but may be due to the presence of joints revealed in some angle borings; the difference may also be related to the range of accuracy of both field and laboratory tests of materials of such low hydraulic conductivities.

The similarity between field and laboratory derived values of hydraulic conductivity of the Sangamon Soil developed in ablation till is probably due to the high clay content and the relatively homogeneous nature of this highly fractured weathered zone.

A separate set of monitoring wells has been constructed for water chemistry samples. While water chemistry data are not presently available, cores of the soil materials from these borings were analyzed chemically for organic and inorganic constituents. The distribution of selected contaminants with depth at Nest A is shown in Figure 4 and is representative of the general findings to date. Figure 4 clearly illustrates that the zones of highest contaminant concentration are in the soft ablation till and the weathered basal till (Vandalia till zones 2 and 3, respectively), with the majority occurring in the soft ablation zone. The results of the field injection tests at this nest indicate that the soft ablation zone has the highest hydraulic conductivity and this probably accounts for the higher concentrations of contaminants and apparently higher migration rates in this zone.

Figure 5 illustrates a geologic cross section of monitoring well profile V at Trench Area B with the results shown for analysis of purgeable organics from core materials obtained during installation of the monitoring wells. In this case the zone of highest contamination is the brittle, weathered, basal till which occurs near the base of the trenches. No field hydraulic conductivity tests have been conducted at this location so it is not known whether the brittle basal till is more permeable than the soft ablation till at this location of the site. It is clear that the greatest contamination occurs in this zone at Profile V and that the contaminants have migrated more than 20 ft from the trench but less than 60 ft since no contamination was detected at wells V2D, V3D, or V4D.



Material	Average texture (%) sand-silt-clay	Hydraulic conductivity (cm/s) Field Test[1]	Hydraulic conductivity (cm/s) Lab Test[3]
Peoria Loess	5-65-30		1.1×10^{-6}
Roxana Silt			
Sangamon Soil	30-35-35	4.4×10^{-7}	1.6×10^{-7}
Vandalia Till (ablation)	45-40-15	$4.1 \times 10^{-5} - 2.3 \times 10^{-4}$ $9.5 \times 10^{-6} - 2.9 \times 10^{-4}$*	2.0×10^{-7}
Vandalia Till (basal) fractured, few sand lenses	41-40-19	$1.4-1.5 \times 10^{-4}$	2.0×10^{-7}
Vandalia Till (basal) few sand lenses	38-43-19	4.4×10^{-7}	4.1×10^{-9}
Banner Fm. (till)	10-50-40		
Pennsylvanian shale			

[1] Water injection/recession curve tests by ISGS

[3] Samples recompacted

*45° angle hole injection tests

ISGS 1983

Figure 3. Idealized stratigraphic column, results of field and laboratory tests of hydraulic conductivity, and texture of geologic materials at Wilsonville site. Actual trench depths generally ranged from 10 to 20 feet.

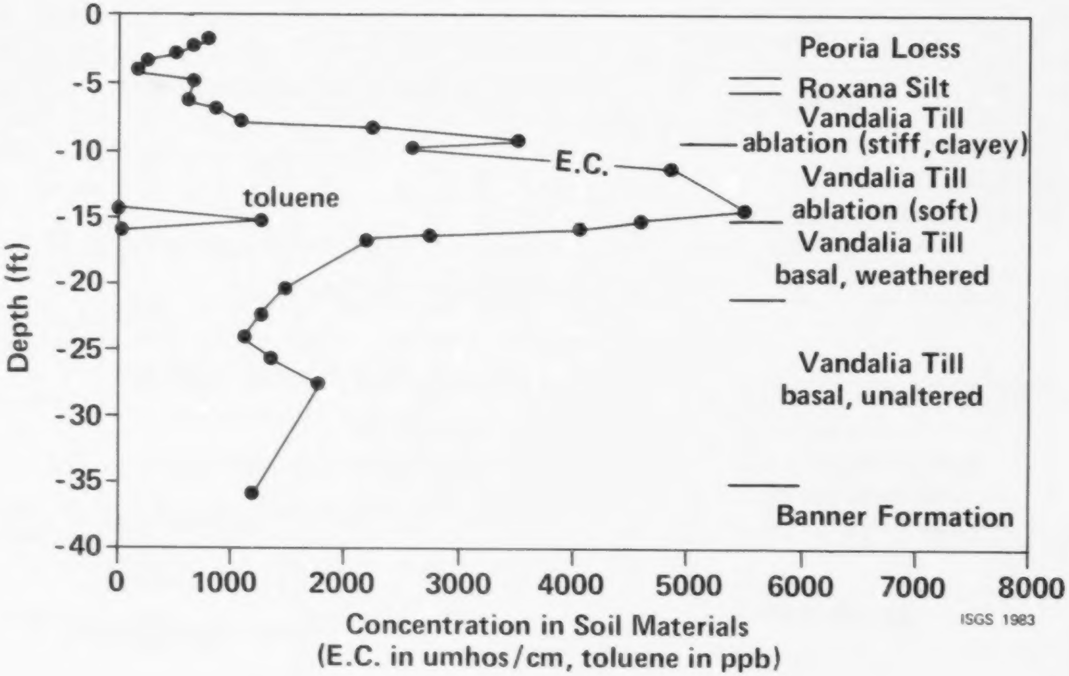


Figure 4. Contaminant distribution with depth at Nest A.

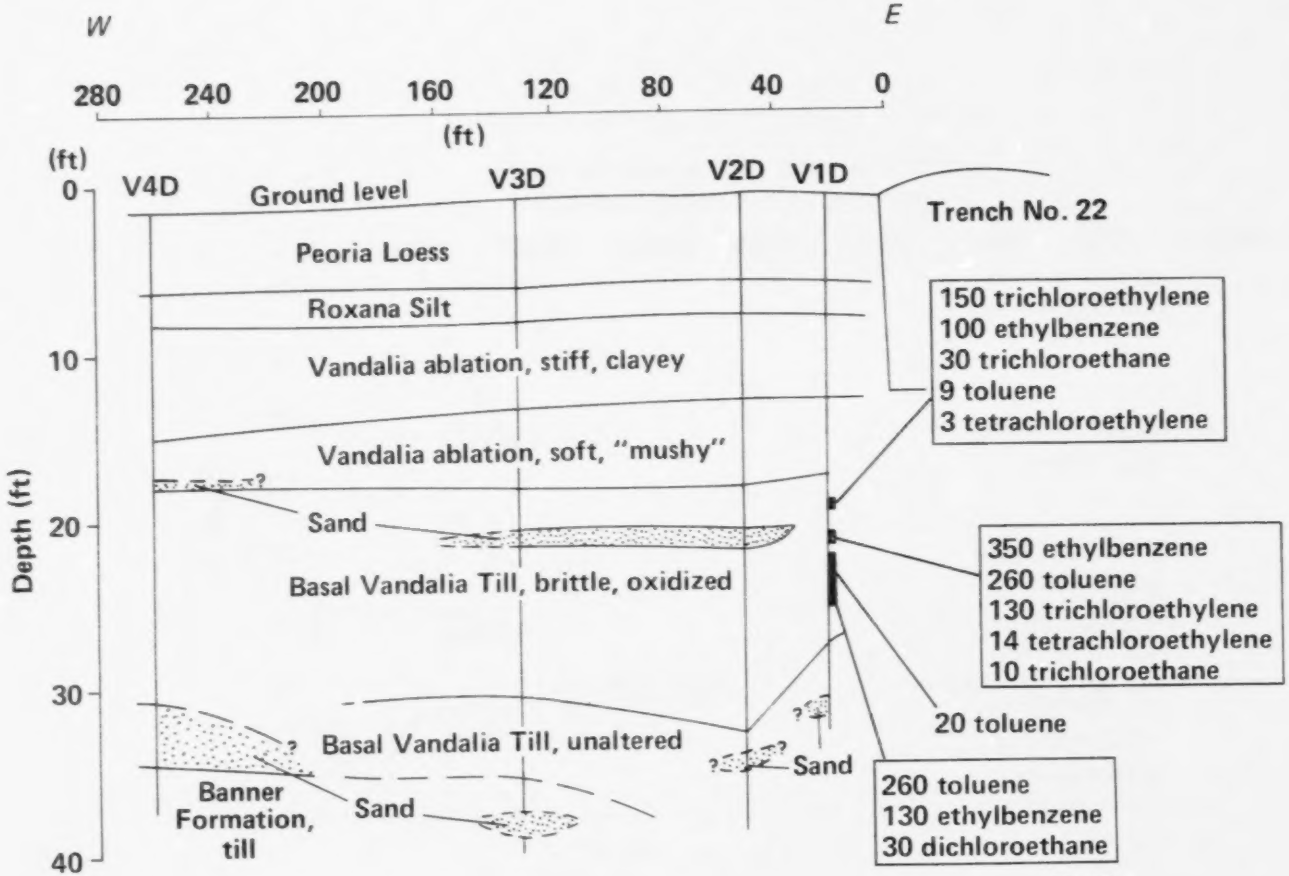


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Figure 5. Profile V cross section, purgeable organic concentrations from drill core soil samples (μg/kg).

CLAY-ORGANIC SOLVENT INTERACTIONS

Organic solvents have been shown by several investigators to increase the hydraulic conductivity of clay soils. Because of the presence of such solvents in the Wilsonville landfill, studies are being conducted as part of this project to identify mechanisms responsible for hydraulic conductivity increases and to develop test procedures that can be used with soils and leachates from the site.

Anderson, Brown, and Green (1982) found much higher permeabilities for soils exposed to various organic solvents. They thought this could be caused by the flocculation of clay particles and by collapse of expandable clay minerals such as smectite. The investigation reported here was designed to assess the relative importance of flocculation and layer collapse as factors in the failure of clay materials used to contain wastes.

Although the glacial materials at Wilsonville contain relatively small amounts of expandable clay minerals, smectite, an expanding mineral, is the ideal mineral to measure changes in interlayer expansion. A Wyoming bentonite variety was chosen for study because it expands to a large enough interlayer spacing in water such that equilibrium spacings of the organic-smectite complex are easily detected and measured. The bentonite was fractionated in water to <2μ by sedimentation. The natural exchangeable cation on this clay is primarily sodium, and osmotic swelling occurs to spacings in excess of 100Å. Smectite in such a swollen state has 10 times as much water as mineral by volume; therefore, the potential for collapse is great.

Gels were made by gently grinding the oven-dried clay with a mortar and pestle and adding water in increments while mixing the paste with a spatula, until the (001) smectite peak became diffused at >25Å. A duplicate large sample of gel was made, mixed, and allowed to age. Chemical agents were then added to the gel or small samples of the gel were immersed in a solvent and allowed to age. This sample could then be used to compare the effects of several different agents.

The treated paste was smeared on a glass slide and X-ray traces were made by immediately scanning the 2-10° 2θ region for appropriate peaks. When using extremely volatile liquids such as acetone, additional liquid was often added during placement of the sample in the X-ray diffractometer. Even with these techniques some samples lost enough volatiles to exhibit a primary, fully expanded peak, and a peak with relatively collapsed interlayer spacing reflecting "dry" material on the sample surface. When adding two or more solvents, it was impossible to measure the exact interlayer composition, and the best that could be done was to carefully control the proportions of solvent addition. In order to obtain results that could be used with confidence, X-ray traces were only used if a simple transformation of (001) spacings from water to the treated stage was observed. Complex X-ray patterns could not be used.

Causes of Layer Collapse

Smectite can undergo layer expansion or collapse due to changes in exchangeable cation or ionic charge (Brindley, 1980, and Theng, 1982) and also when exposed to a host of organic chemicals. Brindley, Wiewiora, and Wiewiora (1969) studied the degree of expansion of Ca-montmorillonite when exposed to several miscible organic compounds. A summary of their findings is presented in Table 1.

When montmorillonite was solvated with water-organic mixtures from 0-100 percent, they found several distinct types of behavior as the proportion of organic increased:

1. osmotic swelling and dispersion,

2. swelling to a greater degree than water,

3. little or no change in swelling for part of the range of mixtures,

4. progressive, step-wise, or immediate collapse to about the d-spacing associated with pure organic, and

5. development of mixed-layered or poorly defined complexes.

The montmorillonite-water-acetone system is an excellent example of the result of varying the water-organic solvent ratio. The stable and well-crystallized montmorillonite-water complex is swollen to 19Å. Even additions of about 1 mole percent acetone, cause free osmotic swelling and dispersion. "From about 20-60 mole percent acetone, the clay is expanded

TABLE 1. X-RAY "d"-SPACING OF A Ca-MONTMORILLONITE TREATED WITH ORGANIC CHEMICALS

H_2O	1-10%R*	20-50%R*	60-90%R*	100%R*	R	Dielectric constant
19	50+	26.5**	22**	17.3	acetone	20.7
19	23**	18	18	17.8	n-propanol	20.1
19	22**	18	18	14	1,5 pentanediol	
19	29.5**	21**	17	17	ethanol	24.3
19	19.3	17	17	16.8	ethylene glycol	37.7
19	19	19	16.5	16.3	methanol	32.6
19	15	15	15	15	dioxane, morpholine	2.2 7.3

Modified from Brindley, G. W., K. Wiewiora, and Andrzej Wiewiora (1969).

*%R is the percent of organic chemical when water makes up the rest of the system, i.e. %R + %H_2O = 100%.

**Mixed-layered structure or broad peak that lacks perfect ordered spacings.

to about 26.5Å with very irregular diffraction maxima, and in the range 80-90 mole percent, the spacing is about 22Å and still highly irregular" (Brindley, Wiewiora, and Wiewiora, 1969). When exposed to pure acetone, the mineral further collapsed to about 17.3Å compared to 19Å in water alone. For the compounds studied by them, three general types of behavior were observed: (1) Some organics such as acetone, propanol, ethanol, 1,5 -pentanediol, and ethylene glycol caused relative expansion of the clay, followed by progressive or step-wise collapse to a spacing less than water (19Å); (2) methanol addition led to a stable spacing of about 19Å up to about 50 mole percent, followed by a sudden collapse to ∿17Å from 50-100 mole percent (Brindley, Wiewiora, and Wiewiora, 1969); and (3) dioxane and morpholine was found to cause immediate collapse at 1-100 percent organic to ∿15Å regular structures. Brindley (1980) further studied montmorillonite with Li^+, Na^+, K^+, Rb^+, Cs^+, Mg^{+2}, Ca^{+2}, Sr^{+2}, Ba^{+2}, and Pb^{+2} as exchangeable cations and after solvation with a range of water-dimethylsulfoxide (DMSO) concentrations. Pure DMSO gave spacings ∿19Å, so that Cs-montmorillonite was observed to expand from 12.5Å in pure water to 19Å in pure DMSO. Montmorillonite exchanged with K^+ was observed to swell osmotically from 0-10 mole percent DMSO, collapse to 15Å from 10-35 mole percent DMSO, and swell to 19Å from 40-100 percent DMSO.

Table 2 shows the large potential for expansion and collapse of montmorillonite gels in several solvents. Dispersion is usually associated with expansion in these experiments, but it is unclear whether this behavior is universal. Similarly, all of the gels that collapsed on organic contact turned into hard, flocculated, and cracked aggregates that showed no tendency to disperse in the solvent. It is also important to note that the procedure used by Brindley, Wiewiora, and Wiewiora (1969), and Brindley (1980) is different from that used by the author. The previous works began with <2μ sedimented slides that were dried in air. The experiments reported

TABLE 2. EFFECTS OF CHEMICAL TREATMENTS ON EXPANSION OF WYOMING BENTONITE

Chemical Treatment	001 d-Spacing Å	State of Sample
Set 1		
control gel	20.5-35 diffuse	dispersed gel
gel and ethylene glycol	17.0 sharp	completely flocculated, hard mass
gel and dimethyl formamide	23.3 sharp	caused suspension of gel
gel and methanol	20.1 sharp	completely flocculated, hard mass
gel and ethanol	22.1 sharp	completely flocculated, hard mass
gel and acetone	38.4 diffuse	dispersed gel
gel and CCl_4	20.5-35 diffuse	probably didn't replace water?
Set 2		
H_2O	20.1	
H_2O (air dry 20 min.)	20.1 + 16.4	
Air Dry (H_2O*)	12.8	
Methanol (+H_2O*)	16.8	
Toluene (+H_2O*)	12.8	rough sample; flocculated
CCl_4 (H_2O*)	13.8	rough sample; flocculated
Acetone (H_2O*)	21.6 + 17.7	
Ethanol (+H_2O*)	17.0	rough sample; flocculated
H_2O (very wet)	35Å	
H_2O + 4 drops ethanol	20.1	
H_2O + 8 drops ethanol	22.7?	
H_2O + 12 drops ethanol	broad peaks	
H_2O + 16 drops ethanol	21.0	

*Dry sample contains about 1 interlayer water layer at start of experiment.

here have employed montmorillonite gels that were already swollen with water.

The previous discussion of water-clay-organic interactions seems to explain the hydraulic conductivity results of Anderson et al. (1982) very well. When soils were exposed to some organics, cracks developed and there was an immediate increase in flow. Acetone treatment showed lower conductivity at first, and then cracking occurred and flow increased. This behavior would seem to match the changes observed by Brindley, Wiewiora, and Wiewiora (1969). This mechanism is possibly a contributing cause to the migration of organic contaminants observed at the Wilsonville site.

ENGINEERING GEOLOGY STUDIES - TRENCH COVERS AND SUBSIDENCE

The objectives of the trench cover study are twofold. The first is to determine the mechanisms for failure of the covers. The study may identify soil materials which would be most suitable for construction of future trench covers. Also, improved construction and burial techniques may be identified which would improve cover stability. The second objective is to determine if the continuity of the trench covers and in-situ soil materials were disturbed by mine subsidence. The site is situated over an abandoned coal mine and failure of the underground mine openings has caused subsidence of the ground surface elsewhere in the region. Court testimony hypothesized that subsidence of the trenches at the site could cause fractures which would result in increased seepage from the trenches.

A review of technical literature concerning design and construction of trench covers by Herzog, et al. (1981) shows that the rate of migration of wastes from burial trenches is probably related significantly to the rate of infiltration of precipitation through the covers. One function of constructing trench covers with sloping surfaces is to reduce the rate of infiltration and to improve runoff. Sags, depressions, or "sinkholes" which develop in the cover after construction interrupt the flow of the runoff and allow more water to infiltrate through the cover or in the case of a "sinkhole" to flow unimpeded into the trench.

Field Work and Surveys

A field survey of the trench areas made prior to the exhumation of the wastes showed no obvious tension crack patterns typical of mine subsidence areas. The survey did show the presence of six depressions ("sinkholes") located within the area of the trenches as shown in Figure 6. A precision (third order) monumented survey net was established over the entire site. Additional monuments and instruments were installed at special locations to monitor settlement, differential settlement, and tilt of some of the trench covers. For example at trench 19, to better study changes near the sinkhole in the west end, additional monuments were tied into the precision survey system.

Samples of trench cover material were collected for testing the susceptibility of cover materials to internal erosion or piping.

Susceptibility of trench cover materials and their components of loess and till to piping are summarized in Table 3. Loess is variously susceptible to internal erosion whereas till is relatively unsusceptible. One test used for this determination is the pinhole test developed by Sherard, et al. (1976) for testing materials used in earthen dams by simulating water flow through a small opening in a compacted sample of soil material. A modification of the Sherard pinhole test was used for this study. Tests were run at 2 in, 7 in, and 15 in heads. No tests were run beyond the 15 in hydraulic head.

The pinhole tests show dramatic variability in resistance of the loess samples to erosion which gave test results of D-1 and ND-2 (highly susceptible and unsusceptible, respectively, see Table 3). The results tests of Vandalia till samples with classifications of ND 1 or 2 indicate high resistance to erosion. The trench cover No. 5 samples tended to be highly resistant, while trench cover No. 25 tended to be only moderately resistant. Figure 6 shows a "sinkhole" depression in the cover of trench No. 25, whereas trench No. 5 does not. Preliminary results suggest that the pinhole test will be a useful test for determining susceptibility to piping in trench covers.

Continued Monitoring and Laboratory Testing

The precision survey was designed to measure very small movements which commonly continue to occur several months after a mine subsidence event. Movements of the monuments which may be caused by natural causes such as freeze/thaw or shrink/swell of soil materials must be taken into account. A subsidence monitoring program should extend through all seasons (usually at least one calendar year) before definitive conclusions can be drawn. Examining data from only one season could easily lead to errors because of the size of the signigicant movements.

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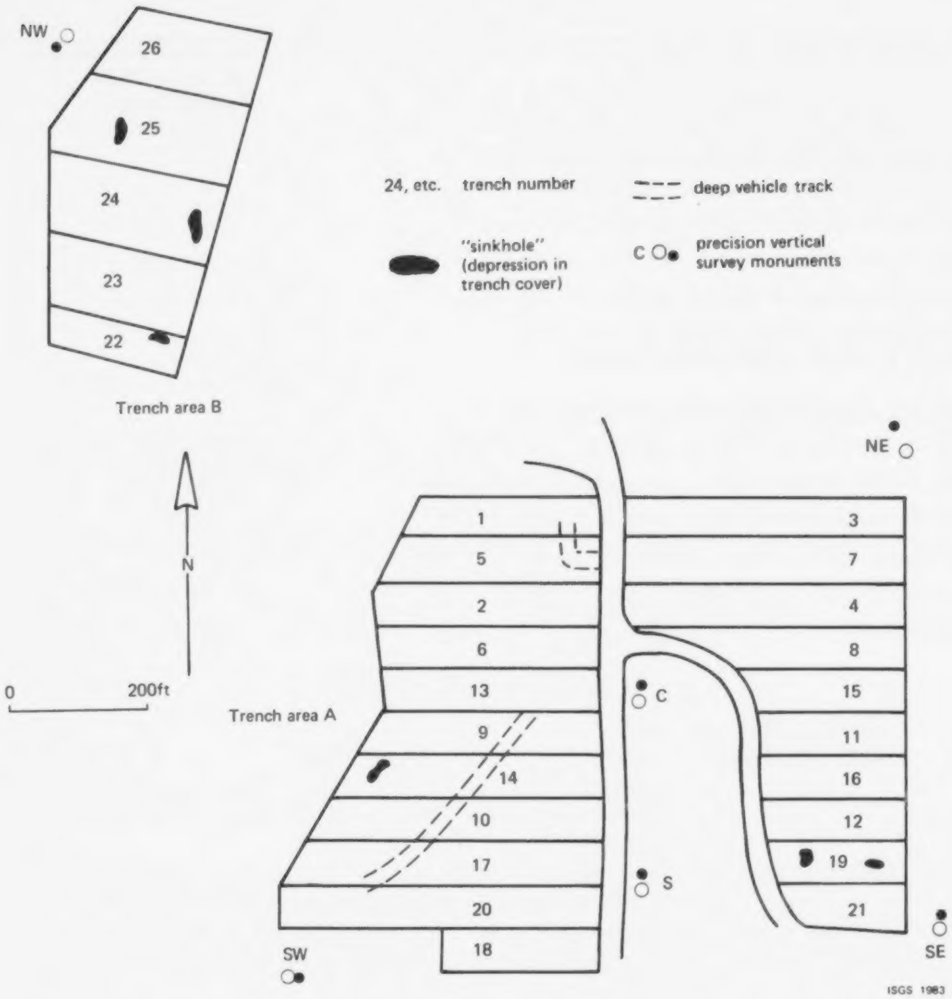

Figure 6. Sketch of waste disposal trenches at Wilsonville, IL showing six "sinkholes" mapped on August 11, 1982 by M. M. Killey.

TABLE 3. RESULTS OF PINHOLE TESTS OF TRENCH COVER SAMPLES AND NEARBY NATURAL MATERIALS

Sample Description	Pinhole Test Classification
Trench 5, disturbed mixed cover material	
1.5 feet below ground level, middle of Trench 5	ND-3
2 feet below ground level, middle of Trench 5	ND 1 or 2
3 feet below ground level, middle of Trench 5	ND 1 or 2
4 feet below ground level, middle of Trench 5	ND 1 or 2
6.0 feet below ground level, adjacent to Trench 5 undisturbed soil (loess?)	ND-2
Trench 25, disturbed mixed cover material	
1 foot below ground level, west end Trench 25	ND 2 or 3
2 feet below ground level, west end Trench 25	ND-4
5 feet below ground level, west end Trench 25	ND-3
Loess taken from roadcut south of waste disposal site	D-1
Vandalia Till ablation phase, (two tests)	ND 1 or 2
Vandalia Till basal phase, (two tests)	ND-3

CLASSIFICATION SUMMARY*

Pinhole Test Classification*	Definition
ND-1 and ND-2	Unsusceptible to piping, highly erosion-resistant, clear or barely visible colored water discharge from sample.
ND-3 and ND-4	Intermediate soils, slight but easily visible cloudy or colored water discharge from sample.
D-1 and D-2	Highly susceptible to piping, highly erodable, distinct cloudy or colored water discharge from sample.

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*Adapted from Sherard et al. (1976)

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FABRICATION OF WELDED POLYETHYLENE ENCAPSULATES TO SECURE DRUMS CONTAINING HAZARDOUS WASTES

S. L. Unger, B. M. Eliash, R. W. Telles, H. R. Lubowitz
Environmental Protection Polymers, Inc.
Hawthorne, California 90250

ABSTRACT

Corroding 208-liter (55-gallon) steel drums holding hazardous wastes present a threat to man and the environment, a threat that is intensified in uncontrolled disposal sites. To prepare such drums for secure and safe transportation and disposal, a process was developed to encapsulate them in polyethylene overpacks. Process features are custom designed polyethylene overpacks and a friction welding apparatus to produce seamless overpack seals.

The process provides a unique option for encapsulating corroding steel drums with polyethylene. Other means to encapsulate drums with polyethylene are expected to yield products with poor properties due to inferior overpack closures which cannot sustain leak tight conditions under stresses expected during use. By friction welding, encapsulates are sealed seam-free and testing results show high mechanical performance. In addition to seam-free closures, the encapsulates exhibit increased corrosion resistance. Verification of corrosion resistance is based upon published work concerning polyethylene. High performance of closures was confirmed by mechanical testing and microscopic observation.

These improved characteristics are estimated to be available at comparatively moderate costs. Polyethylene overpacks are estimated to be competitive in cost with steel overpacks. A projected cost of $70 per drum was determined for encapsulating drums in an uncontrolled disposal site at the rate of 100,000 drums per year.

INTRODUCTION

In previous laboratory studies hazardous, unconfined contaminant particulates, sludges, and small corroding containers holding toxic substances were encapsulated in 6.35 mm (1/4 in.) thick, seam-free polyethylene (PE) jackets. (8,4,6) These encapsulated contaminants resisted delocalization by harsh aqueous leachates that simulated extreme case conditions potentially found in a landfill. When management of 208-liter (55-gallon) corroding steel drums was considered, it was proposed to reinforce them by encapsulation with jackets similar to those previously investigated.

The method selected for encapsulating the drums with PE was to seal them in PE overpacks. The PE overpacks were prepared by rotomolding powdered PE into 6.35 mm (1/4 in.)-thick wall receivers and matching covers. The drums were inserted into the receivers and the receivers sealed, seam-free, by friction welding the covers onto the receivers.

Rotomolding was selected for producing overpacks because rotomolding is a cost-effective method for fabricating large PE holding tanks. It also permitted custom molding for simple low-cost overpacks for drums. With these fabricating advantages, the cost of PE overpacks is estimated to be competitive to the cost of steel overpacks. However, the rotomolding industry could not produce the open-head overpacks with high-performance closures needed for better drum management. Therefore, friction welding of covers to the receivers was considered as a potential method to produce high performance leak tight seals.

Overpacks could be produced readily where they are needed. Rotational molding shops are located through the U.S. We estimate that production of 100,000 overpacks per year, the estimated amount needed to initially address the uncontrolled disposal site problem, would engage only a small fraction of the production capacity of the rotomolding industry.

PURPOSE

The purpose of this work is to demonstrate a superior method for overpacking steel containers of hazardous waste. Previous work had indicated the potential for using PE to produce an overpack superior to steel. In order to demonstrate the technology, it was necessary to design and fabricate PE overpacks and a friction welding apparatus, since they were not commercially available. Improved service performance would be expected because PE encapsulates would not be subject to the prevalent failure mechanisms of steel drums and steel overpacks: corrosion of the container and failure of the closure.(2,3)

The superiority of plastic over steel to resist corrosion has been well documented. Seam-free closures, rather than closures employing bolt rings, threads, gaskets, etc., are features not readily realizable with steel. Seam-free encapsulates would be expected to exhibit significantly improved leak tight performance, particularly when they are subject to lateral compression. Furthermore, the PE overpacks are estimated to be competitive with steel overpacks.

APPROACH

The technical approach taken was to adapt cost-effective, commodity plastics and the advantages of rotomolding to produce a superior overpack for managing corroding steel drums holding toxic materials. Much of the data on use of plastics for encapsulating hazardous waste and its expected performance was taken from previous studies and the literature. Based upon this the overpack process was designed involving two major considerations:

- Selecting plastics and designing overpacks.
- Selecting and/or designing a closure mechanism with superior performance features compared to conventional closure devices.

Plastics

Polyolefins, particularly high density and linear low density polyethylene, were selected for fabricating overpacks because such materials are well characterized, mass-produced, comparatively low-in-cost, and provide a unique combination of properties: Broad chemical compatibility, corrosion resistance, mechanical resilience, and toughness.(7) Other resins are also potentially suitable for overpacks, e.g., polypropylene, polyamide, polybutylene, and polyvinylidene fluoride; but these materials were not addressed in this program because we judged polyethylene to have the broadest applicability at lowest cost. Nevertheless, we reviewed the properties of resins to establish their suitability to be rotomolded and friction welded in order to employ them to manage contaminants which may not be compatible with polyethylene. Examples of wastes which could be managed by nylon overpacks include those wet by solvents such as methylethyl ketone.

In comparison to steel overpacks, polyethylene overpacks offer effective management of acidic waste materials. These materials are highly corrosive to steel; to improve the performance of steel overpacks for these applications, the overpacks are lined with a thin layer of polyethylene or coated with an epoxy phenolic resin.

The dimensions of the overpacks are based upon two design criteria: encasement of steel drums and sealing them by friction welding. The overpack dimensions are 66 cm (26 in.) inside diameter and 97.2 cm (38 1/4 in.) high. These dimensions well provide space between the outside of the drum and the inside of the overpack to accommodate partially distorted drums and incorporate absorbents. The wall thickness of 6.35 mm (1/4 in.) is consistent with the wall thickness of 85 gallon free-standing holding banks and commercial PE drums. An overpack weighs approximately 45 lbs; in contrast, a steel overpack weighs 78 lbs.

The welding operations are aided by two features in the overpack design: (1) the configuration of the lip of the receiver and (2) the ribbed structure of the cover. The lip provides a welding surface upon which the cover is fused to the receiver. The width of the welding surface was 1.9 cm (3/4 in.), approximately three times the wall thickness of the overpacks, thereby assuring a secured closure. The ribbed structure of the cover provides the means to engage the cover to the welding apparatus for welding the cover to the receiver.

Friction Welding

The selection of friction welding to seal the overpacks was based upon commercial friction welding practice used to produce high performance joining of relatively small circular plastic parts. The feature of the technique judged particularly advantageous in managing drums in the field is the capability to rapidly join the plastic receivers and covers without exposing the joints to the air. Other plastic welding techniques such as butt welding do not exclude air contact with joint bonding areas, therefore not preventing potential oxidation of the resins and reduced joint strengths.

PROBLEMS ENCOUNTERED

The major problem encountered in the work was the absence of data and practice concerning friction welding large diameter parts. The literature provided criteria for equipment design and friction welding operations only for small diameter part friction welding. An extrapolation of the data to effect bonding of large diameter in parts from that of friction welding of small diameters parts indicated novel design features affect bonding and machine balancing were required in order to assure high performance and readily reproducible sealing of PE overpacks. Design and experimental emphasis was given to the configuration of the bonding surfaces and the drivetrain of the equipment, thereby a successful friction welding apparatus was developed which does not require precision balancing.

RESULTS

Specifically, the results of our work are addressed in this section under the following topics:

- Design and fabrication of friction welding apparatus
- Determination of operational procedures and parameters
- Evaluation of overpacks and welded joints
- Economic analysis of an overpacking operation
- Field Demonstration

Apparatus

The friction welding apparatus was designed with provisions for transportation by truck or railcar (Fig. 1). The apparatus consists of five subsystems designed for encapsulating drum in the field: frame, drivetrain, hydraulic power unit, drum positioning mechanism, and electronic controls.

The frame houses the hydraulic power unit, welding drivetrain, electric junction box, and drum clamps. The frame also provides a platform so that overpacks can be loaded onto and removed from the apparatus by conventional equipment such as forklifts or drum hoists. The frame is pallet mounted so that the apparatus can be moved by forklift to different on-site locations. The frame was welded from 2 in. structural steel and 1/2 in. thick deckplate. The frame dimensions are 120 in. long x 48 in. wide x 82 in. high.

The drivetrain serves to rotate the PE overpack cover under pressure. (Fig. 2). The drivetrain consists of a hydraulic motor, driveshaft, coupling, tapered

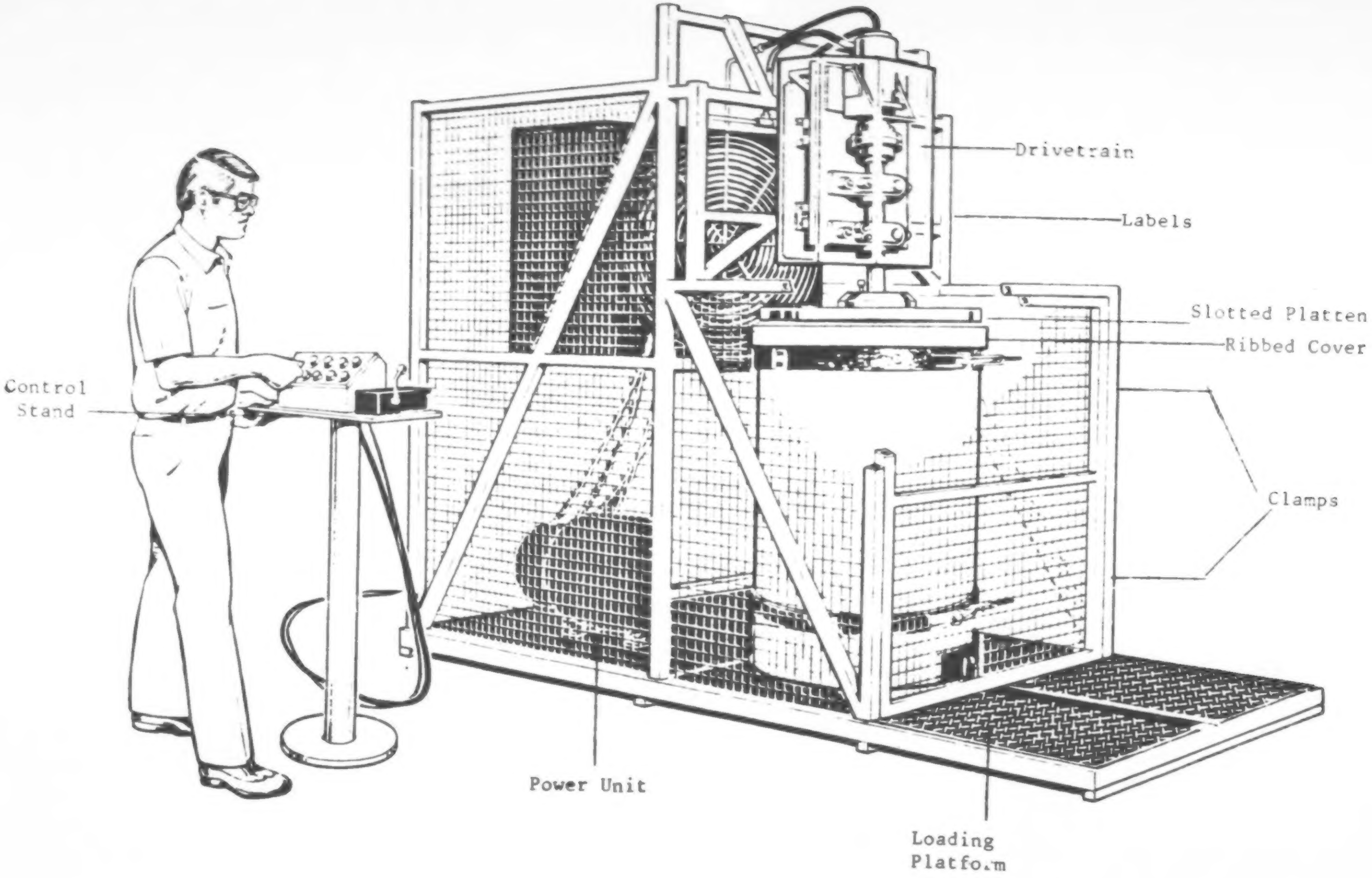

Fig. 1 EPP Overpack Welding Unit

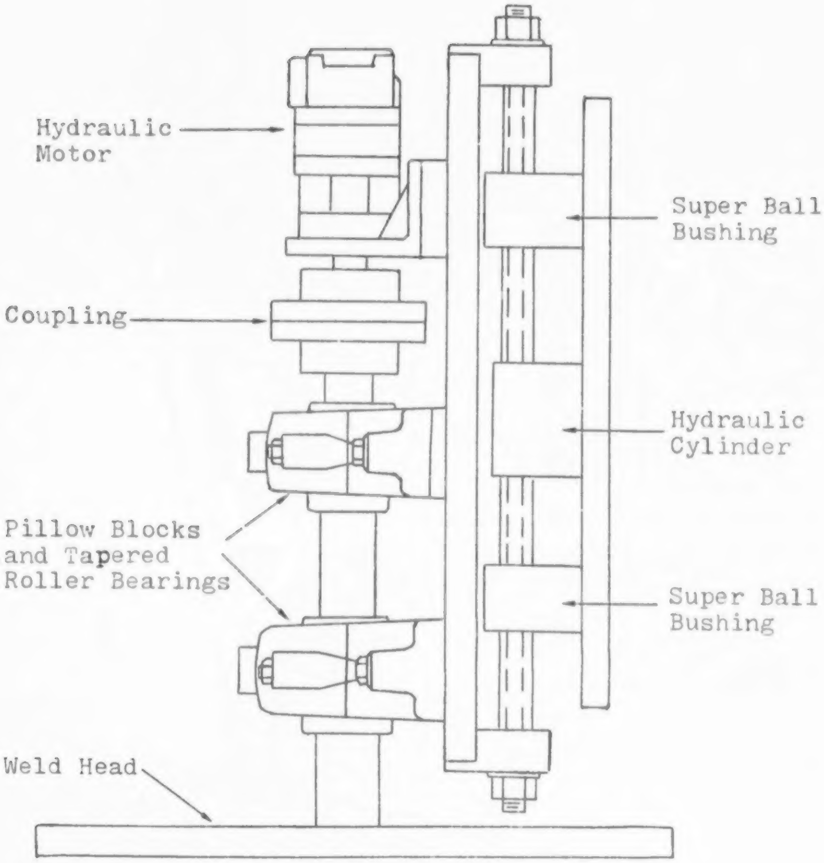

Figure 2. Schematic of Welding Unit Drivetrain.

roller bearings, and machined weld head. The weld head engages the ribbed overpack cover and rotates it to generate frictional heat. Rotation of the weld head is effected by the hydraulic motor through the driveshaft. The bearings reduce vibrations and stabilize the assembly. The drivetrain is mounted on a linear positioning table to advance and retract the weld head. The table is actuated by a hydraulic cylinder which also provides weld pressure. The drivetrain was fabricated from standard mechanical components except for the machine platen and custom-size positioning table.

The hydraulic power unit provides the two principle requirements of the friction-welding technique: rotation of the cover and application of the welding pressure. The power unit consists of two circuits; the power circuit actuates the hydraulic motor and the pressure circuit actuates the cylinder. Each circuit is supplied by a separate pump; however, both pumps are mounted on the same shaft driven by a 40 h.p. electric motor. The power circuit is close-looped, allowing use of a small reservoir (17 gallon). The circuits are controlled by solenoid valves and a variable volume pump in the power unit.

The drum positioning mechanism indexes the overpack from the loading platform to the welding cage. By use of clamshell clamps which are bolted to the frame, the mechanism positions the overpack under the weld-head. The clamps are then closed to secure the receivers during the welding process.

The electronic controls allow operation of the apparatus by a single individual from a remote location. The control box is mounted on a steel stand and can be positioned up to 25 feet from the welding apparatus. Switches control four servovalves in the hydraulic circuits to select low or high weld pressure, advance or retract the linear positioning table, and deactivate the spin and press circuits. The rotational speed is controlled by a joystick mounted on the stand.

Operations

The procedure used for overpacking drums with welded polyethylene overpacks involve four major steps:

o Loaded receivers are placed on loading area of the welding unit.

o Traverse the loaded receiver under the weld head of the welding unit. Place cover on the receiver and clamp receiver in place.

o Weld cover to receiver by rotating at specified speed, pressure, and time.

o Unclamp overpack and traverse finished encapsulate to the loading areas.

Table 1 presents the range of welding parameters which were used to produce high-performance bonds.

Table 1. OPERATING PARAMETERS
USED IN FRICTION-WELDING
OF OVERPACKS

Processing Parameter		Range of Values
Rotation speed	-	280-350 rpm
Welding pressure	-	75 psig* (line pressure) 5 psi (weld pressure)
Spinning time	-	30-45 seconds
Curing time	-	2-7 minutes
Cure pressure	-	75 psig* (line pressure) 5 psi (weld pressure)

* Relates to line gauge on apparatus

Evaluations

Tests of the welded encapsulate were performed to evaluate both the entire overpack and welded bond. The polyethylene overpacks were water tight and exhibited mechanical performance exceeding that of steel overpacks. A hydrostatic burst test showed that the welded polyethylene encapsulates were stronger than steel overpacks. They withstood an average of 17.8 psi whereas

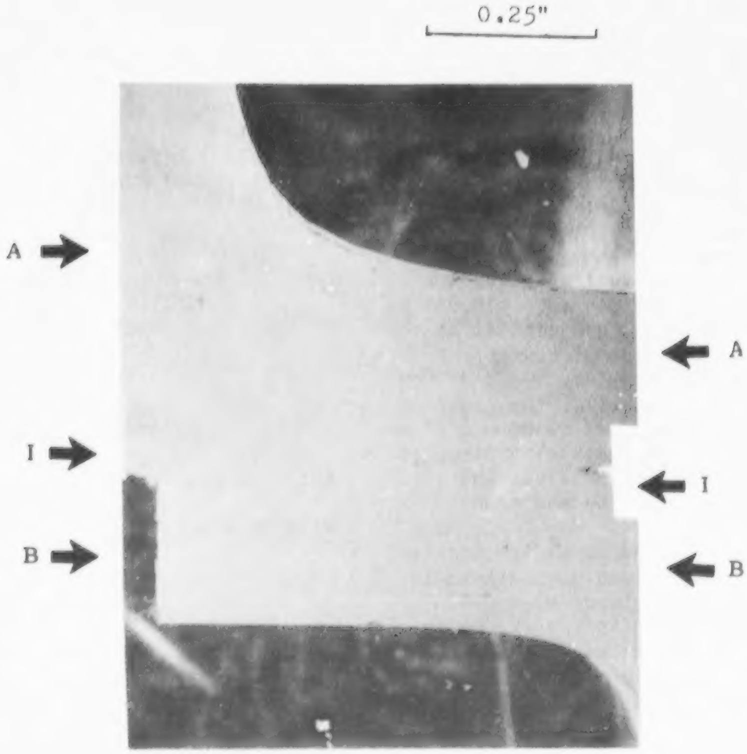

Figure 3. Transmission Optical Micrograph (5X) of Friction Weld. Regions A, B, I are natural HDPE cover, natural HDPE receiver, and weld interface, respectively.

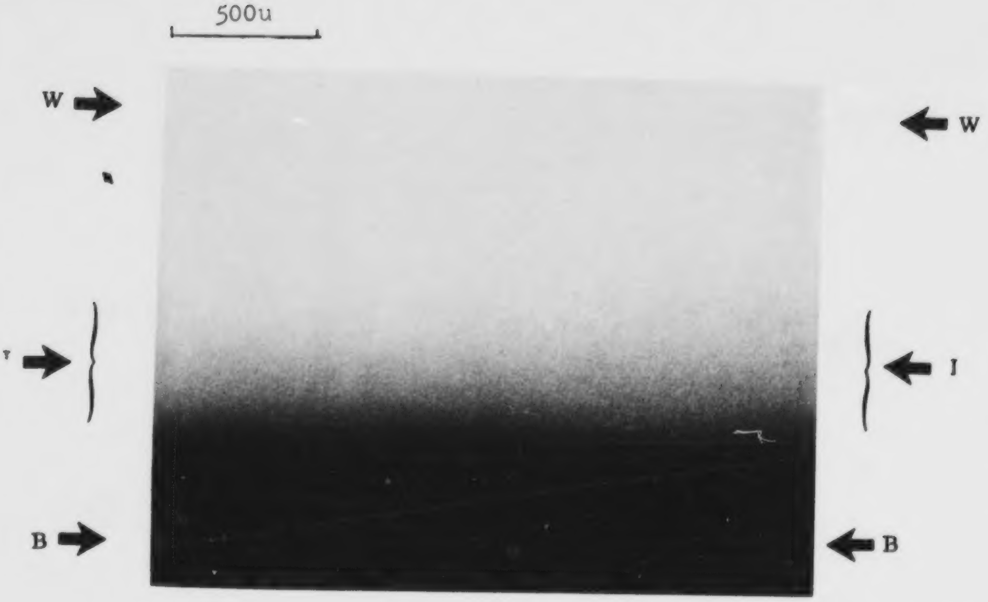

Figure 4. Transmission Optical Micrograph (50X) of Friction Weld. Regions W, B, I are natural (white) HDPE cover, UV-stabilized (black) receiver, and welded interfacial region respectively.

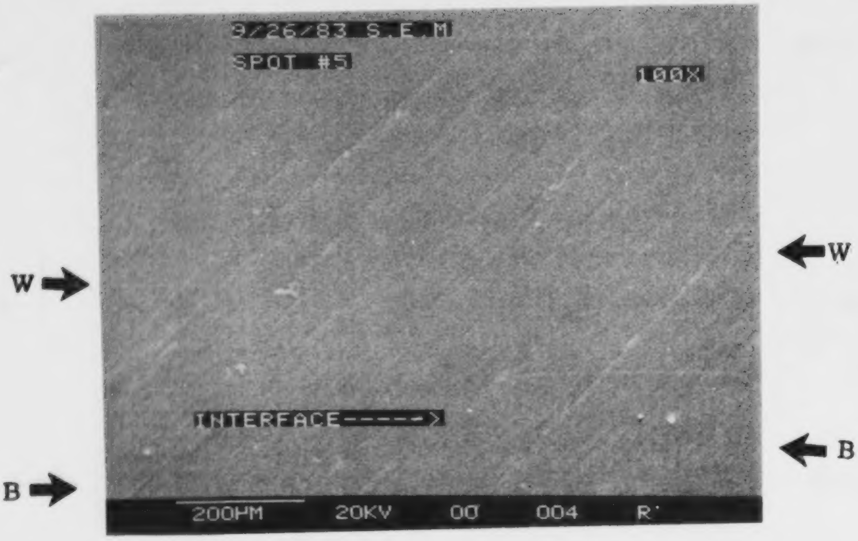

Figure 5. Scanning Electron Micrograph (SEM) of Friction Weld. Regions W and B are natural (white) HDPE cover and UV-stabilized (black) HDPE receiver, respectively. (Weld interface is along arrow path; 45° angled striation results from polishing during sample preparation).

steel overpacks are rated to 15.0 psi. Overpacks subjected to the burst test did not fail at the welded interface.

Sections of the weld were subject to tensile testing, and the welds were examined visually and micrographically. Tensile pulls showed that a "proper" weld was achieved by friction welding. The specimen consistently and without exception yielded at the toe of the weld and not at the interface.

Thin cross sections of the weld were examined by preparing transmission optical micrographs. Figure 3 is a 5X magnification that showed the weld to be a continuous and void-free cohesive bond. The weld length measured 2 1/2 times greater than the wall thickness of the overpack. No distinct weld line was observed, indicating that good wet-out and thorough mixing of the 50X magnification of a welded specimen prepared from a natural (white) HDPE cover and a UV-stabilized (black) HDPE receiver. This micrograph shows the welded interface to be formed by a gradual and homogenous mix of each parent material. The thickness of the interfacial region was approximately 560 microns. Moveover, no "hairline" (distinct interface) between the joined materials was observed. Figure 5 is a scanning electron micrograph (SEM) of the weld interface magnified 100X. the SEM shows that there was no discernable difference in the surface morphologies or the interface and the parent materials. Interfaces featuring uniform surface morphology without a "hairline," differentiates friction welds from heat-seams and butt-weld. (5) We postulated that advanced mechanical performance exhibited in hydrostatic and tensile tests was due to the formation of cohesive bonds characterized by large, homogeneous interfaces.

Economics

An economic analysis of a full-scale drum management process showed polyethylene encapsulates to be competitive with steel overpacks. The economic analysis was based on managing 100,000 drums per year at an uncontrolled disposal site. The analysis included equipment costs, material costs, and labor. Equipment included conventional drum handling equipment and four overpacking apparatures. Materials included the overpacks delivered to the site, and the labor requirements included six men operating 300 days per year.

Process costs were estimated to be $7.0 million or $70 per encapsulated drum. Materials comprised over 90% of the process costs; costs could be reduced by using scrap polyethylene to fabricate overpacks. Currently, costs for steel overpacks range from $62.5 to $120 per overpack, depending on location.

Process Demonstration

The welded polyethylene overpack was demonstrated at the CECOS, International waste treatment facility in Cincinnati, Ohio during November 1-12, 1983. The demonstration involved encapsulating and disposing of approximately 100 drums of waste materials. The demonstration showed the feasibility of the welded polyethylene overpack for management of a wide range of toxic materials including PCB contaminated sludges, solidified flammable sludges and paint manufacturing sludges. Fig. 6 shows loading a 55-gallon drum into an overpack by use of a drum grappler. Fig. 7 shows welding the cover onto the receiver with the welding apparatus.

During the demonstration, the polyethylene overpacks were used for in-container solidification of sludges. The polyethylene overpack can also be used as a container for long-term storage or transportation of wastes.

ACKNOWLEDGEMENTS

Environmental Protection Polymers, Inc. would like to acknowledge Schober's Machine and Engineering for fabricating the welding apparatus, and Ronco Plastic for fabricating the overpacks.

This research was supported by the U.S. Environmental Protection Agency, Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, Cincinnati, Ohio, under contract #68-03-3144. EPP would like to acknowledge the guidance of the project monitor, Mr. Carlton C. Wiles.

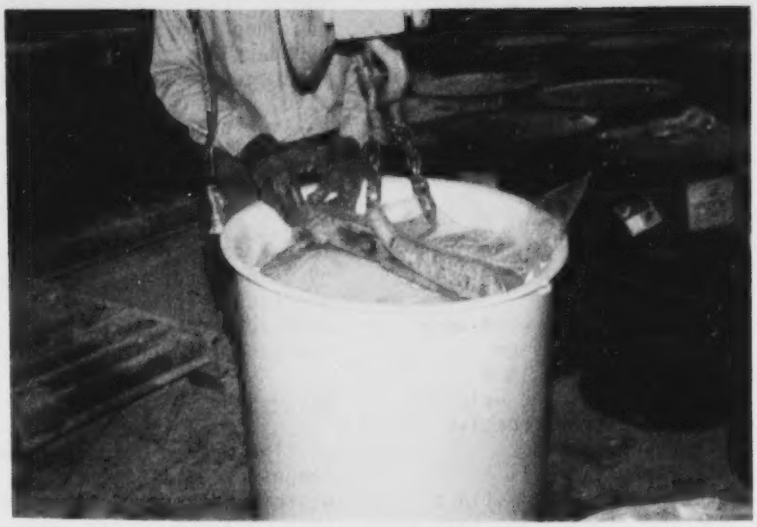

Figure 6. Loading 55-gal. Drum into Polyethylene Overpack

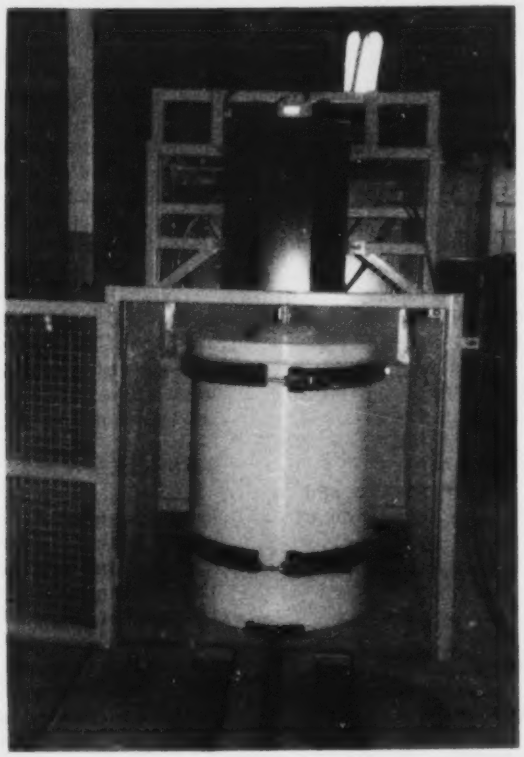

Figure 7. Welding Cover onto Receiver During Process Demonstration.

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SIMPLIFIED METHODS FOR THE EVALUATION OF REMEDIAL ACTION PERFORMANCE

by
Stuart M. Brown
Anderson-Nichols and Company
Palo Alto, CA 94303

ABSTRACT

Simplified methods useful in evaluating the performance of subsurface and waste control remedial measures are identified and discussed. These methods include the following types of analytical and semi-analytical ground-water flow and transport solutions, and associated methods: 1) well hydraulics; 2) drain hydraulics; 3) ground-water mounding; 4) superposition; 5) equivalent sections, incremental methods and corrections for anisotropy; 6) conformal mapping; and 7) contaminant transport.

Hand-held calculator and micro-computer programs have been written for some of the available methods. The general types of programs that are available and the advantages they offer are discussed. Sources for these programs are also identified.

An analysis of the effectiveness a ground-water pumping remedial action with and without an impermeable barrier is presented to illustrate the use of selected methods. The methods applied in the analysis include those for well hydraulics, superposition and contaminant transport.

The simplified methods that are discussed can be used by EPA and state Superfund staff involved in the review of Remedial Action Management Plans and Engineering Feasibility Studies. They can also be used by site contractors to screen potentially feasible remedial action alternatives and, in some cases, to conduct detailed analyses of alternatives and to develop conceptual designs.

INTRODUCTION

The National Contingency Plan (NCP) sets forth a process for the evaluation and selection of remedial actions at uncontrolled hazardous waste disposal sites. One element in this process is the Engineering Feasibility Study. This study is itself a staged process that involves the screening of remedial action technologies, the detailed analysis of potentially feasible alternatives and the conceptual design of the most cost-effective alternative.

During the screening stage, the intent is to reduce the large number of potential technologies to a workable number by identifying those that are clearly infeasible or inappropriate. Best engineering judgement supplemented by order-of-magnitude estimates of remedial action performance are usually sufficient during this stage.

The intent of the detailed analysis stage is to identify the most cost-effective action. Again, best engineering judgement supplemented by some level of analysis will provide much of the basis for the decision. The required level of analysis will be a function of: 1) the complexity of the site, 2) the resources available for the Engineering Feasibility Study and 3) the potential impacts associated with failing to fully meet site clean-up goals.

The final stage in the feasibility study process is to develop a conceptual design for the most cost-effective remedial action alternative. Again, depending upon the factors discussed above and the complexity of the selected alternative, the level of required analysis will vary.

PURPOSE

Recognizing the need for both simplified and sophisticated methods to support decision-making throughout each stage of the feasibility study process, the Environmental Protection Agency Municipal Environmental Research Laboratory (MERL) in Cincinnati, Ohio initiated a research project to develop two complimentary levels of remedial action assessment methods. The first level is composed of relatively sophisticated computer codes. This level is to be used predominantly for detailed analysis and conceptual design by site contractors who have the expertise and experience required to properly apply surface runoff and unsaturated and saturated ground-water computer codes. The second level is a collection of simplified methods. These methods are meant to be used by state and Federal staff to review engineering feasibility study results, and by site contractors for purposes of screening analysis and, possibly, detailed analysis and conceptual design.

This paper overviews the second level of remedial action assessment methods; the first level is presented in a companion report by Brown et al. (3). While the companion report covers computer codes applicable to the assessment of surface, subsurface and waste control actions, this paper focuses on methods applicable only to the assessment of selected subsurface and waste control actions (e.g., pumping/injection wells, interceptor trenches, capping and bioreclamation). The methods discussed in this paper are largely analytical or semi-analytical solutions for ground-water flow and transport, and simplified methods that use these solutions.

APPROACH

The approach followed in conducting this research involved:

1. A review of the available analytical and semi-analytical solutions and associated methods for evaluating ground-water flow and transport,
2. The identification of those methods applicable to the evaluation of remedial action performance, and
3. The identification of those methods that have been programmed for use on hand-held calculators and micro-computers.

RESULTS

Types of Simplified Methods

During the 1950's, the development of analytical and semi-analytical solutions for flow in ground-water systems dominated the literature. Even though attention shifted to numerical modeling in the 60's, progress continued in the development of analytical methods (16). As a result, there currently exists a large number of solutions and associated simplified methods, many of which are applicable to the assessment of certain subsurface and waste control remedial action technologies. The following types of simplified methods can be used: 1) well hydraulics; 2) drain hydraulics; 3) ground-water mounding; 4) superposition; 5) equivalent sections, incremental methods and corrections for anisotropy; 6) conformal mapping; and 7) contaminant transport.

The one area that has received the greatest attention in terms of the development of analytical solutions is the area of well hydraulics. Numerous solutions have been developed to calculate the change in piezometric head or water table elevation resulting from the introduction of a well. The most general solutions are for horizontal, homogeneous isotropic aquifers of constant thickness and infinite extent. The well is generally assumed to be fully penetrating and to have an infinitesimally small diameter.

These basic assumptions often limit the use of these more general solutions in certain situations. Fortunately, a number of analytical solutions based on other assumptions have been developed. Solutions have been derived for anisotropic conditions and a range of possible well configurations, including wells with a finite diameter, wells with storage capacity, flowing wells, and partially penetrating wells. Walton (17) provides a reasonably complete inventory of available analytical well hydraulics solutions for confined, leaky and water table aquifer systems.

Drains are collection systems of finite length that can be used, like wells, to intercept contaminated ground water and to depress the water table. They can have a number of configurations ranging from fully penetrating, vertical trenches to partially penetrating ditches to perforated pipes. Unlike wells, drains are almost always installed in water table aquifers.

The complete mathematical description of time-varying flow to drains in water table aquifers is nonlinear and intractable largely because of the effect of the moving water table boundary. As a result, simplifications based on the Dupuit-Forchheimer assumptions and linearization must be made before analytical expressions can be derived. Cohen and Miller (4) recently compiled a large number of available analytical expressions for flow to drains. While most of the solutions are for water table aquifers, a number have also been derived for confined and leaky aquifers.

Large quantities of leachate can produce a mound in the water table below certain types of waste disposal facilities and remedial action technologies. Mounding of a water table aquifer can have a major impact on local ground-water flow patterns and the resultant movement of contaminants.

At least one analytical method has been developed for use in evaluating changes in water table elevations as a result of recharge from an areal source. Hantush (6) derived a method for an areal source, rectangular or circular in configuration. The method can be used to estimate changes in water table elevations at different radial distances away from the center of the source area.

Many of the available analytical solutions were derived for single wells or drains with constant flow rates or heads in aquifers of infinite extent. Since few aquifers satisfy these conditions, it is often necessary to consider the hydraulics associated with and interactions between multiple wells and drains and nearby boundaries. This is particularly true for the evaluation of remedial action performance where wells, drains, and impermeable barriers are often used conjunctively. It is the principle of superposition that makes it possible to combine the solutions for single wells and/or drains to obtain solutions for multiple well and drain systems with variable flow rates and head conditions. One special type of superposition, the method of images, makes it possible to add the effects of boundaries like streams, ground-water divides and impermeable zones to solutions for aquifers of infinite extent.

Most of the available analytical solutions are also based on the assumption that flow occurs in isotropic and homogeneous media. This assumption is often limiting because all real ground-water systems exhibit some degree of heterogeneity and anisotropy. Fortunatley, there are practical ways to circumvent this limitation through the use of equivalent sections and incremental methods, and by making corrections for anisotropy. The use of equivalent sections basically involves converting the irregular geometry of a real world ground-water system into an equivalent system with a regular geometry. In making the conversion to an equivalent system it is often necessary to account for layered and trending heterogeneities. Layered heterogeneities are vertical changes in media properties; trending hetergeneities are horizontal changes. Incremental methods involve dividing an aquifer into regions with relatively uniform properties and then applying an analytical solution in a step-wise fashion to each region. Bear (1) recommends this approach for water table aquifers with appreciable variations in head. In many systems there may be distinct differences between horizontal and vertical hydraulic conductivities. In these cases, corrections need to be made before solutions based on isotropic conditions can be used. Huisman and Olsthoorn (7) present a series of formulas for making corrections for anisotropy.

Conformal mapping is a method for deriving analytical solutions by transforming a problem from one geometrical domain for which a solution is needed to one for which a solution can be obtained. This method has been used to derive expressions for selected two-dimensional ground-water flow problems involving relatively complicated geometries. A major disadvantage of the method is that it is mathematically involved, and often produces fairly complex analytical solutions. One advantage of conformal mapping is that it can be used to derive a solution for flow under partially penetrating impermeable barriers or barriers that are keyed into leaky formations. None of the methods discussed thus far can provide such a solution. The theory behind the method is discussed by Harr (5).

A number of analytical solutions for contaminant transport have been developed. Most of them are based on the classical convection-dispersion equation. In addition, several semi-analytical methods have also been developed. The analytical solutions based on the convection-dispersion equation are consolidated in several key publications. van Genuchten and Alves (15) provide derivations for a relatively complete set of one-dimensional solutions. Walton (17) presents several one-dimensional solutions and a number of radial flow solutions involving single injection and withdrawal wells with and without regional flow. Other good sources include Bear (1) and Javandel et al. (8). One type of semi-analytical method is based on the complex velocity potential concept. Like superposition, this concept involves separating a complex flow field that itself is intractable into a series of simple flow fields for which tractable solutions are available. Javandel et al. (8) provide a procedure for constructing complex velocity potentials. The other type of semi-analytical method for contaminant transport is based on a simple numerical technique discussed by Bear (1). This technique involves tracking the movement of one or more particles of water with time. The rate and direction of particle movement at any location in the ground-water flow field is estimated by adding the component pore water velocities for nearby pumping and injection wells with the regional pore water velocity.

Remedial Action Evaluation with Simplified Methods

There are a large number of remedial action technologies that can be implemented at uncontrolled hazardous waste sites. These actions can be classified as either surface, subsurface or waste control measures (3). Many of the available technologies are described in remedial action handbooks like those by JRB (9) and SCS Engineers (14). The simplified methods discussed in the previous section can be used to evaluate many of these technologies. Since these methods are applicable only to flow and contaminant transport in saturated ground-water systems, however, only those measures having an effect on the saturated zone can be evaluated. This mainly includes subsurface and waste control measures.

Table 1 lists each of the measures that can be evaluated, and the specific methods that can be used (2). It is important to recognize that many of the subsurface and waste control measures can have different configurations and design objectives. Impermeable barriers, for instance, can be installed upgradient, downgradient and completely around a site. They can be partially penetrating (i.e., hanging) or fully penetrating (i.e., keyed-in). They can be used to lower the water table, divert uncontaminated ground water around a site, or preclude further migration of contaminated ground water.

TABLE 1. SIMPLIFIED METHODS APPLICABLE TO THE EVALUATION OF SUBSURFACE AND WASTE CONTROL REMEDIAL MEASURES

REMEDIAL ACTIONS	Well Hydraulics	Drain Hydraulics	Ground-Water Mounding	Super-position	Equivalent Sections, Incremental Methods and Corrections for Anisotropy	Conformal Mapping	Contaminant Transport
Subsurface Control							
Capping and Top Liners			X				X
Recharge Basins and Ditches		X	X	X			X
Subsurface Drains, Ditches, Bottom Liners			X				X
Impermeable Barriers				X		X	
Ground-Water Pumping	X			X	X		X
Interceptor Trenches		X		X	X		X
Waste Control							
Permeable Treatment Beds							
Bioreclamation	X			X	X		X
Chemical Injection	X			X	X		X
Solution Mining	X			X	X		X
Excavation/Hydraulic Dredging			X				X

X - Indicates Method is Applicable

It is also important to recognize that there are a number of important limitations and key assumptions that must be considered when using the methods in Table 1 to conduct a practical evaluation of remedial action performance:

1. Many of the analytical and semi-analytical solutions were derived for specific types of aquifers (e.g., confined, leaky or water table) with highly idealized characteristics.

2. Many of the solutions were also derived for highly idealized ground-water flow patterns.

3. Many of the solutions were derived fro specific well or drain configurations.

These and other limitations preclude the complete, detailed analysis of all remedial action design objectives and configurations. Changes in water table elevations or piezometric heads associated with the implementation of most subsurface and waste control remedial measures can generally be evaluated. Changes in ground-water flow patterns can generally also be evaluated for most remedial measures, especially those that involve wells or drains. Changes in contaminant movement, however, are more difficult to fully evaluate.

Despite their apparent simplicity, considerable judgement and experience are required to evaluate remedial action performance with simplified methods. In applying these methods it is important to recognize the tradeoffs that are being made between the ease of application and the accuracy with which these methods can simulate the effects of implementing different remedial actions.

Available Hand-Held Calculator and Micro-Computer Programs

The use of many of the available analytical and semi-analytical methods to solve ground-water problems of practical interest will generally require numerous, repetitive calculations. An evaluation of the cone of depression for a single pumping well, for instance, will involve solving one of the well hydraulics equations for a number of radial distances away from the well at different points in time. If the cone of depression for a number of wells is of interest, the drawdown for each well will have to be calculated and then summed to obtain the total drawdown.

With the recent development of relatively powerful, programmable hand-held calculators and micro-computers, the work involved in using many of the methods is greatly reduced. Calculators and micro-computers can rapidly perform a large number of repetitive calculations in minutes that would otherwise require hours or days. As a result, the level of manpower required to solve a given problem is greatly reduced.

Calculators and micro-computers also have several other advantages. First, they can reduce the need for tables and graphs that are commonly required to solve analytical expressions. Values for the "well functions" in most well hydraulics equations generally have to be obtained from tables or graphs. While the required tables and graphs can be found in many ground-water textbooks and related publications, some of the "well functions" can be approximated by series expansions or mathematical functions that are easily solved on a calculator. Many of the functions contained in other types of analytical methods can also be approximated or solved directly with calculators. In addition, simple integration schemes that would require numerous, tedious calculations to solve by hand can also be used to quickly solve certain analytical equations.

Another advantage is that calculators and micro-computers offer peripherals that aid in the analysis of remedial actions. The programs required to solve different analytical expressions can be stored on magnetic cards, magnetic tape of disks. When an analysis is required the programs can be loaded rapidly. This reduces the level of effort required to key in a program or to make repetitive key strokes on a non-programmable calculator. Results of different analyses can be stored for use later or printed immediately. This reduces the level of effort involved in transcribing results.

The final advantage is that programmable calculators and, to a lesser extent, micro-computers are readily available. Most site contractors and many state and Federal Superfund staff have access to them.

It is important to note that there are a large number of programs currently available, particularly for hand-held calculators, and more are being written all the time. Listings for some of these programs have been published in the open literature (11, 12, 18, 19, 20) and in different reports (10, 13, 17). Other programs can be obtained from their developers. The International Ground Water Modeling Center (IGWMC), Holcomb Research Institute, Butler University, Indianapolis, Indiana provides a clearinghouse for many of the available programs.

Example Analysis of Remedial Action Performance with Selected Simplified Methods

A number of abandoned underground storage tanks were discovered to have lost their contents over a period of years. A detailed field sampling program found that the ground-water system was extensively contaminated. Figure 1 shows the current extent of contamination and the characteristics of the underlying aquifer.

The screening of remedial actions during the Engineering Feasibility Study suggested that the plume could be captured with a line of pumping wells located near the leading edge of the plume. It also suggested that an impermeable barrier completely surrounding the plume might act to expedite the clean-up action of the pumping wells. Thus, it was decided to analyze the time required for plume extraction with and without an impermeable barrier.

The initial remedial action configuration selected for analysis was a line of three pumping wells without an impermeable barrier. The wells were located 100 ft upgradient from the leading edge of the plume, and each well was assumed to be pumped at a rate of 20 gpm.

To estimate the plume extraction time for this configuration, a semi-analytical transport method was used. The method uses a simple numerical technique to tract the movement of a particle of water with time. A well hydraulics solution incorporated in the method is used to estimate the rate and direction of particle movement away from injection wells and towards pumping wells. The method also allows for superposition. Thus, the effects of any number of wells and a uniform regional flow component can be considered in a single analysis.

The actual application of the method involved releasing particles from a number of locations along the perimeter of the plume. The movement of each particle was tracked over time until it arrived at one of the wells. The location of each particle at the end of selected time increments was noted. These locations were then used to estimate the approximate location of the perimeter of the plume at the end of each time increment.

Figure 2 shows the position of the plume 0, 10, 20, 40, 80 and 120 days after the initiation of pumping. The results show that it takes approximately the same length of time for contaminants to travel from the storage tanks to the wells as it does for contaminants to travel from the leading edge of the plume to the wells. This is because the net ground-water velocity upgradient of the wells is the sum of the regional velocity and the velocity induced by the pumping action of the wells. Downgradient the net velocity is smaller because it is the difference between the two velocities.

The results also show that most of the plume can be captured in about 120 days. It is important to recognize, however, that this timeframe is based on the assumption that the contaminants are "water coincident." That is, they are not retarded in their movement relative to the movement of the ground water. The timeframes in this example would have to be extended for contaminants that are retarded by using an appropriate retardation factor. It is also important to recognize that this analysis neglects

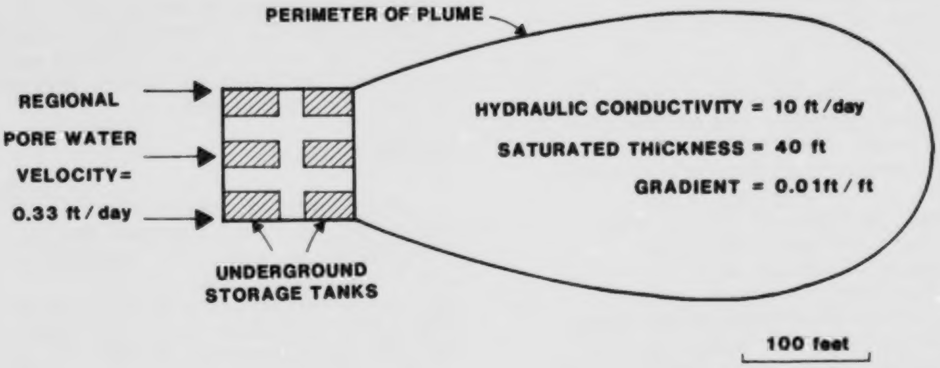

Figure 1. Extent of contamination and aquifer characteristics.

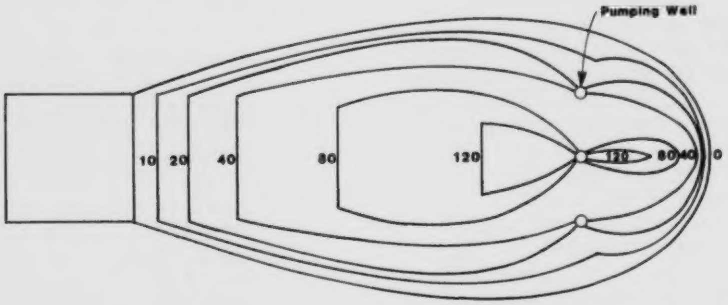

Figure 2. Plume position 0, 10, 20, 40, 80, and 120 days after initiation of pumping without an impermeable barrier (pumping rate of 20gpm).

the effects of dispersion. The perimeter of the plume is assumed to behave like a "sharp front."

The impact of installing an impermeable barrier around the plume was examined with the same simplified method. Figure 3 shows the resulting configuration of the remedial action alternative.

To simulate the impact of installing an impermeable barrier, the method of images was used. The analysis was simplified somewhat by only considering the effects of the upgradient and downgradient portions of the barrier. That is, the sides were neglected. Figure 4 shows the image well configuration used to create these barriers. Since they are assumed to be infinite in extent, the "real aquifer" (i.e., the portion of the aquifer inside the barrier) has the configuration of a semi-infinite strip. A complete representation of the barrier could be obtained by using a more complex image well configuration.

Particles were again released from the perimeter of the plume and their movement towards the recovery wells was tracked with time. Since the barrier eliminates the regional ground-water flow component, it was assumed that the pumping rate of the wells could be reduced to 10 gpm even though the wells were left in the same location. Figure 5 shows the estimated position of the plume after 0, 10, 20, 40, 80, 120, 160, 320, 480 and 640 days. These results show that the barrier wall reduces the time required to capture contaminants downgradient from the wells, but increases the time required to capture contaminants between the wells and the storage tanks. In part, this is due to the use of a reduced pumping rate. However, it is also due to the fact that there is no regional component of velocity inside the impermeable barrier. The velocity due to the pumping wells is all that is affecting contaminant movement; this velocity is very small near the facility.

Centering the wells within the plume, possibly along a line parallel to the main axis of the plume, would provide for more rapid removal, as would increasing the pumping rate. The efficiency of this and other well and impermeable barrier configurations can easily be evaluated using this type of approach.

A large number of calculations were required to generate the results in Figures 2 and 5. A hand-held calculator program for an HP 41C calculator was used to reduce the level of effort involved in conducting the analysis.

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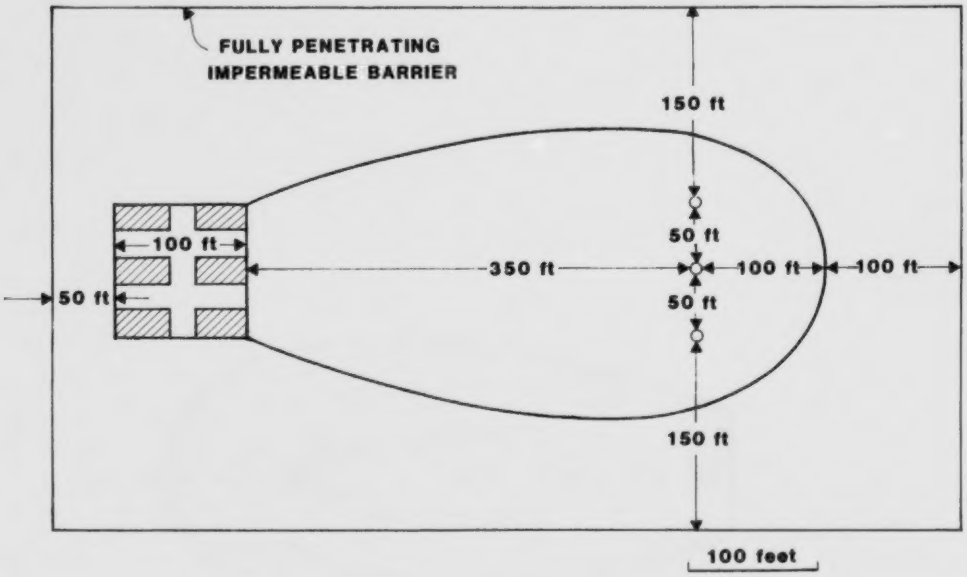

Figure 3. Remedial action configuration for the ground-water pumping system with an impermeable barrier.

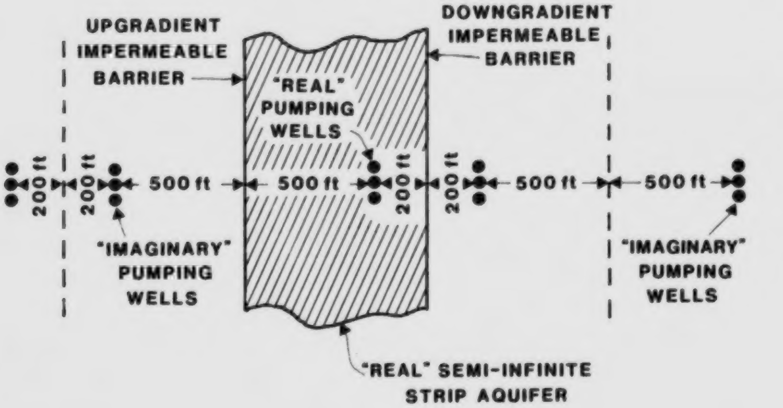
UPGRADIENT IMPERMEABLE BARRIER
DOWNGRADIENT IMPERMEABLE BARRIER
"REAL" PUMPING WELLS
200 ft
200 ft
500 ft
500 ft
200 ft
200 ft
500 ft
500 ft
"IMAGINARY" PUMPING WELLS
"IMAGINARY" PUMPING WELLS
"REAL" SEMI-INFINITE STRIP AQUIFER

Figure 4. Image well configuration for the impermeable barrier.

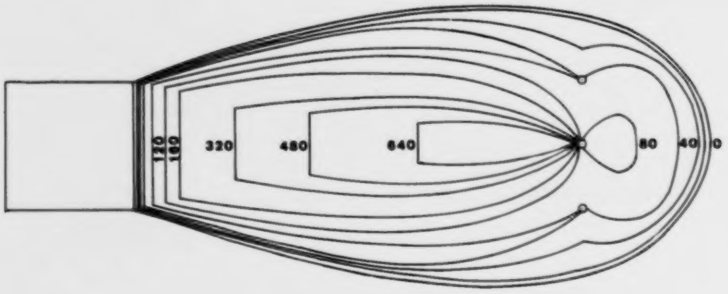

Figure 5. Plume position 0, 10, 20, 40, 80, 160, 320, 480 and 640 days after initiation of pumping with an impermeable barrier (pumping rate of 10gpm).

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COSTS OF REMEDIAL ACTIONS AT UNCONTROLLED HAZARDOUS WASTE SITES
WORKER HEALTH AND SAFETY CONSIDERATIONS

John M. Lippitt, R.S.
James J. Walsh, P.E.
Anthony J. DiPuccio, P.E.
SCS Engineers
Covington, Kentucky

ABSTRACT

Costing of remedial actions at hazardous waste sites requires a determination of incremental costs for protection of worker health and safety. The study presented was designed to identify and estimate incremental health and safety costs for worker protection. Cost estimates were obtained from five hazardous waste site cleanup contractors in response to six hazardous waste site scenarios. Four degree-of-hazard conditions were costed for each scenario. Ranges of percent increases for health and safety considerations over base construction costs are presented along with estimates of the impact of temperature extremes on costs.

INTRODUCTION

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) was enacted in December 1980. Provisions contained in Item 2 Section 105 require the development of cost ranges for various types of hazardous waste site remedial actions. The project presented in this paper represents part of the research efforts of the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) to fulfill the requirements in Section 105.

PURPOSE

The development of costs of hazardous waste site remedial actions requires an evaluation of the increased costs incurred for protection of worker health and safety. In previous studies, costs associated with health and safety were either not included or not uniformly identifiable as separate costs. The purpose of this study was to:

1. Identify categories of health and safety costs.

2. Collect and compile health and safety cost estimates and determine a range of costs which can be encountered on hazardous waste sites.

3. Calculate percentage incremental health and safety cost adjustment factors.

4. Identify factors which impact health and safety costs and should be considered for future study and evaluation.

STUDY DESIGN AND APPROACH

Initial data collection was based on reviews of case studies, bid documents for Superfund sites, and a telephone survey of firms and regulatory agencies. After reviewing available data and the summaries of telephone interviews, it was determined that health and safety costs could not be readily identified. Normal accounting practices did not distinguish many health and safety costs. Such costs were routinely incorporated into general categories such as labor rates, equipment O&M costs, and overhead expenditures. In addition, extensive analysis of cost data from existing sites was viewed by many contractors as extremely sensitive due to competitive and proprietary considerations. On the other hand, most of the contacts felt that general discussions of costs would be of little value because of site-specific considerations which impact on the overall costs and particularly health and safety costs. As a result, it was concluded that realistic, but ficticious, hazardous waste site scenarios would provide the best format for providing and evaluating cost estimates for remedial action unit operations. In fact, several of the contacts indicated they felt it was the only reasonable approach.

Six hazardous waste site scenarios were developed to be representative of three basic types of sites: (1) subsurface burial, (2) surface impoundments, and (3) above-grade storage. Whenever possible, these scenarios were developed based on actual cleanup operations either completed, in progress, or planned for the future. This approach was adopted to ensure that the scenarios would reflect realistic site conditions while providing a means of controlling site variables which could impact cost estimates.

Contractors providing cost estimates were instructed to provide cost estimates for each unit operation under the conditions set forth in the scenario and costs representative of conducting the same activity if the hazardous wastes were not on-site (i.e., base construction costs). In order to identify the relative impact of variations in degree-of-hazard conditions, contractors were also instructed to provide cost estimates based on three other modifications of hazard conditions. The hazard conditions described were designed to parallel degree-of-hazard conditions associated with the four levels of personal protection recommended by the EPA Office of Emergency and Remedial Response (OERR) [1]. Table 1 provides a brief description of the four levels of personal protection (designated as Levels A, B, C, and D in order of decreasing degree-of-hazard conditions). Contractors were instructed to utilize the recommended guidance provided by EPA OERR to determine the level of personal protection required. The modifications were based only on variations of waste characteristics, while all other site conditions and activities remained constant.

One additional factor identified which can significantly impact health and safety costs was ambient temperature. To identify the relative impact of temperature, contractors were instructed to provide an estimate of the cost variations of the total scenario costs estimated for each of the four degree-of-hazard conditions. The cost estimate variations were based on the costs under the range of temperatures given in the scenario and two additional temperature ranges. The result was an estimate of total scenario health and safety costs under the four degree-of-hazard conditions for low (<0°), normal (0-18°C), and high (18-38°C) temperatures. Ambient ranges included wind chill considerations.

TABLE 1. CONDITIONS ASSOCIATED WITH LEVELS OF PERSONAL PROTECTION

1. Level A - requires full encapsulation and protection from any body contact or exposure to materials (i.e., toxic by inhalation and skin absorption).
2. Level B - requires self-contained breathing apparatus (SCBA), and cutaneous or percutaneous exposure to unprotected areas of the body (i.e., neck and back of head) is within acceptable exposure standards (i.e., below harmful concentrations).
3. Level C - hazardous constituents known; protection required for low level concentrations in air; exposure of unprotected body areas (i.e., head, face, and neck) is not harmful.
4. Level D - no identified hazard present, but conditions are monitored and minimal safety equipment is available.
5. No hazard - standard base construction costs.

In providing cost estimates, contractors were requested not to address costs of transportation and disposal. This approach was taken because information was available on transportation and disposal costs and to minimize the amount of cost estimations required of the contractors responding to the scenarios. Since transportation and disposal costs are often included as separate line item costs, separation of these costs in the scenarios is consistent with normal contractor procedures.

Ten health and safety cost components were identified based on literature reviews, previous site observations, discussions with field personnel from state and federal regulatory officials, and discussions with cleanup contractors. Table 2 is a list of the ten health and safety cost categories identified in the scenario guidance/instructions.

The selection of contractors to respond to the scenarios was based on the following criteria:

- Their relative rating provided from the evaluation of the telephone survey results.
- A match of their previous experience with sites similar to one or more of the scenarios.
- The availability of personnel routinely involved in cost estimation and familiar with health and safety requirements on a hazardous waste site.
- Project funding limitations for payment of subcontractors (i.e., site cleanup contractors) to provide cost estimates.

The final selection included seven hazardous waste cleanup contractors responsible for one to three scenarios apiece. Each scenario was assigned to two different contractors for cost estimation.

TABLE 2. HEALTH AND SAFETY COST COMPONENT CATEGORIES

1. Decontamination
2. Emergency Preparedness
3. Hazard Assessment
4. Insurance
5. Manpower Inefficiencies
6. Medical Services/Surveillance
7. Personal Protection
8. Personnel Training
9. Record Keeping
10. Site Security

A questionnaire was also sent to the contractors providing cost estimates. The questionnaire was designed to identify differences in approaches to health and safety considerations which impact costs. The purpose of requesting the information was to provide additional information to assist in determining probable reasons for cost variations anticipated. In addition, contractors were requested to comment on other considerations or differences, if any, that they considered significant.

RESULTS AND DISCUSSIONS

A total of eleven completed remedial action costing scenarios were returned. Two contractors could not provide the requested cost estimates within the required time period due to conflicting work schedules. As a result, cost estimates for Scenario 5 were provided by only one contractor. The remaining Scenarios 1, 2, 3, 4, and 6 were estimated by two contractors apiece.

Cost estimate recording forms received were reviewed and additional information was requested as necessary. Estimated costs were reallocated and adjusted to provide uniform coverage of the ten health and safety cost components identified (see Table 2). Modifications made were reviewed with the respective contractors.

The contractor's cost estimates were compiled and evaluated, then used to calculate a cost per unit range for each remedial action unit operation. Cost per unit calculations were made for health and safety costs at the four degree-of-hazard conditions and for base construction costs. A percentage incremental cost factor was calculated by dividing the health and safety costs per unit for each of the degree-of-hazard conditions by the costs per unit calculated for the base construction cost. The resulting percent ranges of incremental health and safety cost adjustment factors are presented in Table 3. Costs for those remedial action unit operations not costed as part of the six cost scenarios can be estimated based on a comparison of potential worker exposures while conducting remedial action unit operations.

TABLE 3. INCREMENTAL HEALTH AND SAFETY COSTS -- RANGE OF PERCENTAGE ADJUSTMENTS OVER BASE CONSTRUCTION COSTS

Unit Operation	Degree-of-Hazard Conditions			
	Level D	Level C	Level B	Level A
Surface Water Controls:				
1. Surface Sealing - Synthetic Membrane	8-20%	14-24%	17-28%	17-30%
2. Surface Sealing - Clay	9%	19%	24%	27%
3. Surface Sealing - Asphalt	--	--	--	--
4. Surface Sealing - Fly Ash	--	--	--	--
5. Revegetation	5-53%	12-59%	13-60%	14-63%
6. Contour Grading	9-45%	17-57%	22-65%	24-80%
7. Surface Water Diversion Structures	12-57%	20-67%	24-77%	25-83%
8. Basins and Ponds	9-40%	21-54%	28-61%	35-65%
9. Dikes and Berms	7-92%	21-125%	24-131%	26-146%
Ground Water Controls:				
1. Well Point System	10%	17%	21%	28%
2. Deep Well System	--	--	--	--
3. Drain System	9-47%	16-60%	19-66%	27-69%
4. Injection System	--	--	--	--
5. Bentonite Slurry Trench	9%	14%	32%	36%
6. Grout Curtain	--	--	--	--
7. Sheet Piling Cutoff	--	--	--	--
8. Grout Bottom Sealing	--	--	--	--
Gas Migration Controls:				
1. Passive Trench Vents	--	--	--	--
2. Passive Trench Barriers	--	--	--	--
3. Active Gas Extraction Systems	--	--	--	--
Waste Controls:				
1. Chemical Fixation (Solidification)	11-32%	16-41%	17-48%	19-55%
2. Chemical Injection	--	--	--	--
3. Excavation of Wastes/Contaminated Soil	32-545%	44-613%	50-785%	58-1990%
4. Leachate Recirculation	--	--	--	--
5. Treatment of Contaminated Water	7-38%	11-38%	14-43%	14-49%
6. Drum Processing	32-166%	75-192%	50-277%	58-353%
7. Bulk Tank Processing	86-103%	138-158%	173-464%	207-690%
8. Transformer Processing *	--	23-362 %	--	--

* Cost estimates were only requested for Level C.

A general indication of temperature impacts can be drawn from the data provided. The percent variations were based on increases above base construction costs estimated for the moderate 0 to 18°C range. Base construction and health and safety costs increased with higher or lower temperatures. An average variation, shown in Table 4, enables general estimate adjustments relative to the impact of anticipated seasonal or climatic temperature differences.

Several factors which impact cost were identified, but not addressed within the scope of this project. These include:

- Scale Economies
- Regional Differences
- Management Policies and Procedures
- Type and Size of Company

Differeneces in cost estimates provided were apparently due in part to these factors, as well as cost variations experienced during site response and cleanup activities. Use of the data from this report should include evaluation of possible impacts of these factors.

The primary result of this report is a means to adjust remedial action cost estimates to reflect additional costs of health and safety considerations. This may involve adding these health and safety costs to engineering study cost estimates based on standard construction cost estimates, or adjusting cost estimates from actual sites. Adjustments made will reflect the costs associated with variations in the degree-of-hazard conditions on the site being evaluated. Additional applications may include: (1) calculation of costs for alternative applications of a given remedial action based on location and timing, and (2) evaluation of cost-effectiveness of conducting additional site investigation and characterization prior to initiation of remedial response activities.

ACKNOWLEDGEMENTS

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DISCLAIMER

The information and data presented in this paper do not necessarily reflect the views and policy of the U.S. EPA. This paper was based on the Draft Final Report for "Costs of Remedial Actions at Uncontrolled Hazardous Waste Sites -- Worker Health and Safety Considerations" which is currently in the U.S. EPA peer review process.

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TABLE 4. HEALTH AND SAFETY COST MULTIPLIERS AND PERCENT INCREASED COSTS AT DIFFERENT TEMPERATURES

Temperatures		Base Construction Multiplier*	Level D		Level C		Level B		Level A	
° C	°F		H/S Multiplier+	% Increase#	H/S Multiplier+	% Increase#	H/S Multiplier+	% Increase#	H/S Multiplier+	% Increase#
0-18°	32-65°	1.00	0.60	0	0.89	0	1.07	0	1.27	0
18-38°	65-100°	1.06	0.64	8	0.94	14	1.19	17	1.44	19
<0°	<32°	1.09	0.82	11	1.12	15	1.44	15	1.87	17

* H/S (i.e., Health and Safety) cost multiplier of base construction costs at the same temperature.
+ Base construction cost multipliers of base construction costs at 0-18°C (32-65°F).
# Increased health and safety costs from costs at 0-18°C (32-65°F).

EVALUATION OF SYSTEMS TO ACCELERATE STABILIZATION OF WASTE PILES OR DEPOSITS

Emil F. Dul, Robert T. Fellman, Ming F. Kuo
Envirosphere Company
Lyndhurst, N.J. 07071

James F. Roetzer
Woodward-Clyde Consultants
Wayne, N.J. 07470

ABSTRACT

This paper is a project report on work performed by Envirosphere Company under subcontract to JRB Associates' contract No. 68-03-3113 with the USEPA; the task is "Evaluation of Systems to Accelerate Stabilization of Waste Piles or Deposits". The paper presents the results of a seven month study which has led to the conclusion that from the array of treatment methods and delivery/recovery schemes available for in situ subsurface applications, enhanced flushing using surfactants, treatment using biological agents and hydrolysis of waste materials are promising applications. Oxidation of subsurface waste materials does not appear promising. Tables 1, 2 and 3 of this paper present guidance to potential employers of in situ, subsurface treatment systems. These tables relate site and waste characteristics to the propriety of using a particular reagent/delivery-recovery system.

INTRODUCTION

This paper reports on EPA Project No. 68-03-3113, Task 37-2, "Evaluation of Systems to Accelerate Stabilization of Waste Piles or Deposits". This project represents Phase I of a two phase scope of work designed to document the feasibility and effectiveness of engineered approaches to stabilizing and accelerating the detoxification of waste piles and deposits. Phase I, examined presently available technology and site specific waste parameters to determine the limitations imposed by these site and waste specific characteristics on the technologies available. Phase II will present results from bench or pilot scale research applied to waste materials obtained from a site requiring remedial actions and will be undertaken after completion of Phase I.

The Phase I effort concentrated on projecting the possible use of available techniques to sites yet requiring remedial actions by investigating and documenting both techniques historically used to stabilize and accelerate the detoxification of wastes and those believed to be feasibly applicable. In situ treatment rather than immobilization of wastes was emphasized, thus engineering methodologies incorporating 1). biodegradation, 2). hydrolysis, 3). solvent flushing 4). surfactants and 5). oxidizing agents were pursued in detail.

PURPOSE

The Phase I work reported upon in this paper essentially deals with three basic problems:

1) What reagents will be most effectively used to treat which subsurface waste materials?

2) What systems are available for delivery of treatment agents to subsurface deposits (and/or recovery of treated groundwater)?

3) What are the limitations imposed by the site conditions (ie, topography, soil characteristics) and by the waste materials themselves upon the selection of technologies?

The specific goal for Phase I of the project was to develop a specification document capable of prescribing the applicability, limitations and performance expectations for the combination of technology and treatment reagent which could be used in a broad array of site, waste and pollutant combinations. Via the specifications document, waste site and remedial actions associated with low or high probabilities of success would be identified.

APPROACH

Envirosphere pursued a six part program of investigation which consisted essentially of a literature review, a definition of the capabilities and limitation of delivery, recovery and treatment technologies, visits to sites where investigation of remedial actions were underway, a definition of important site and waste characteristics, and an evaluation of remedial technologies. The available data were evaluated to determine classes of organic chemicals amenable to treatment by various potential in situ treatment methods. Potential delivery and recovery systems for these treatment agents were then evaluated across site hydrogeologic characteristics.

Envirosphere then proceeded and developed a specifications manual which identified, to the extent deemed appropriate, given the available data and experience, combinations of delivery/recovery technologies and reagents which have a reasonably high or clearly low probability of success.

PROBLEMS ENCOUNTERED

The single-most important problem encountered by the investigators during this project was the near absence of data and information from specific field experience and applications in a remedial action. For delivery and recovery technologies, a well developed literature exists where traditional applications of these technologies (ie, deep well injection of waste products, spraying of areas for agricultural purposes, flooding, use of infiltration galleries, well point systems etc) are described. Also, for chemical stabilization applications, for example, the use of microorganisms to catabolize waste products or in the case of oxidation of alcohols, aldehydes and ketones to carboxylic acids and cleavage products, well developed literature also exists. However, almost nothing has been published for engineered remedial actions consisting of combinations of delivery systems and reagents in a hazardous waste deposit. Thus, almost all conclusions to be drawn from the study were based upon engineering judgement and scientific approximation. Field calibration and verification of hypotheses by reference to experience was not feasible.

Another important problem encountered in the study was the specification of the degree of homogeneity of the waste deposit. Subsurface deposits contained in drums or in packaging which would impede the flow of water-borne reagents could not be considered as realistic candidates for in situ, subsurface treatment. Thus, only deposits having a relatively uniform permeability not significantly lower than the surrounding medium could be considered as realistic candidates for subsurface in situ treatment.

RESULTS

Systems to accelerate stabilization of waste deposits will require:

(1) selection of a suitable treatment technology which will be compatible with waste composition and site characteristics, and (2) selection of delivery/ recovery methods for the treatment technology compatible with site characteristics and the waste deposit setting.

There are two basic treatment concepts which can be employed, in situ treatment (stabilization through degradation of waste) and flushing methods to accelerate the removal of the contaminants from the deposit for subsequent recovery followed by above surface treatment in a waste treatment system.

Envirosphere reviewed in detail biodegradation, hydrolysis and oxidation as being the treatment methods offering possible opportunity for success in in situ applications. Flushing, and use of surfactants to enhance flushing were also considered to be of sufficient promise to be reviewed in detail. Potential applications of these methods to various classes of organic contaminants are presented in Table 1.

Biological Renovation of Waste Piles or Deposits

Microbes capable of treating many classes of organic chemicals are currently available. These microbes include natural microbial populations, adapted microbial cultures and bioengineered microbial strains (1,2). An extensive compilation of microbes capable of treating various organic chemicals has been developed and is available in the complete project report.

Once the extent of the contamination has been determined and the chemical characterization of the contamination has been carried out, the selected samples should be further characterized chemically to establish the nutritional content of the soils (nitrogen, phosphorus, etc) as a supplemental analysis to the usual array of chemical analyses employed at the site investigation stage of the remedial action.

The proper microorganisms or groups of microbes may then be selected to treat the waste. Commercial firms use their past experience, laboratory screening, onsite test plots, or any combination of these procedures to identify the proper agents for waste site renovation. Independent operators should use similar procedures or should contract with one of the many commercial firms in this field for expert consultation and guidance.

In the process of selecting the appropriate microbes for waste treatment, one must determine the optimum bacteria, emulsifier and fertilizer requirements for optimum waste treatment rates. Microbial agents require the maintenance of sufficient concentrations of nitrogen, phosphorous, trace elements, etc., and a pH range that will support their growth. Knowing the levels of these factors at the site from previous laboratory analysis, one can identify the need for additional fertilizers or buffers required to support microbial growth.

Having identified the above parameters, sufficient quantities of biological agents can be cultured and freeze-dried for transport, storage and use at the site.

In treating surface waste piles or deposits, the waste site is preconditioned by the application of fertilizers, buffers and emulsifiers at rates determined from initial studies. The bacteria are reconstituted with water (preferably site water or a fertilizer solution) and sprayed on the waste site.

Microbial suspensions and emulsifiers are generally applied weekly for the first two weeks, then every two weeks thereafter until wastes are degraded. The biological agents are applied by spraying them evenly over the surface of the waste site, and the area is watered daily to keep the waste moist but not flooded.

If temperature maintenance becomes a problem, the site may be covered with polyethylene, with oxygen supplied through the application of peroxides or other suitable oxygen sources. If anaerobic environments are required (e.g., for reductive dechlorination) the site may require the careful application of additional moisture to saturate the waste, then covering the site with polyethylene to reduce oxygen diffusion into the waste materials. Fertilizers, emulsifiers and buffers are supplied on an as needed basis to maintain maximum degradation rates.

Deep or subsurface waste deposit biological renovation poses problems relating to oxygen supply, temperature, permeability and accessibility not encountered with surface disposal sites. Wells may be established into and below the waste site to deliver a fertilizer and oxygen source (3). Oxygen sources would include injectable solutions of peroxides or air and pure oxygen saturated liquids.

Additional wells around the deposit periphery and into the waste material itself would be required to inject selected microbial preparations and emulsifiers into the waste site. Thus not only is the waste pile treated but any groundwater plumes that may be migrating from the site may be renovated as well. Injection wells should be situated at points peripheral to an area served by a recovery well. The purpose of these injection wells is to surround and infuse the waste deposit with biological agents, fertilizers, emulsifiers and an oxygen source. Flow patterns established between injection and recovery wells should be planned to aid in confining the waste during the renovation process.

The practicality of subsurface waste in situ renovation ultimately depends on soil and waste pile permeability and site temperature. The treatment of waste sites in high clay content soils, wastes containing large concentrations of highly insoluble waste or a combination of these factors may make biological renovation of waste sites impractical. Waste site temperatures are controlled by in situ soil temperatures and biological activity. The applicability of biological treatment of hazardous waste must be assessed on a site by site basis.

Application of Hydrolysis to Waste Deposits

The range of chemical classes potentially treated through acceleration of degradation by base-catalyzed hydrolysis is presented in Table 1 (based on date in 4, 5 and 6). The range of chemical classes in Table 1 includes amides, esters, carbamates, organophosphorus compounds, pesticides and herbicides. Prior to application of this method in the field in a hazardous waste deposit, site specific lab or pilot scale testing should be conducted to demonstrate the effectiveness of the method for the specific chemical/waste deposit matrix. In applying base-catalyzed hydrolysis in the waste deposit, the primary design concern will be the production and maintenance of high pH (9 to 11) conditions with saturation or high moisture content in the waste deposit. In general, for shallow surface deposits, surface application of lime followed by an appropriate surface application of water (eg, spray irrigation) may be appropriate. For other deposits, subsurface delivery or injection of alkaline solutions (eg, NaOH) may be appropriate. In cases where alkaline solutions are applied, proper corrosion resistant equipment should be selected. In addition, for most waste deposits treated by base-catalyzed hydrolysis, leachate recovery methods should be incorporated into system design, since application of the treatment solution may result in flushing of contaminants from the deposit.

Application of Oxidation to Waste Deposits

The potential application of three oxidants (ozone, hydrogen peroxide, and chlorine) to waste deposits has been evaluated. While these agents are reactive with a wide variety of organic compounds, and have demonstrated applications in wastewater treatment, significant problems may preclude their effective implementation as in situ treatment agents for waste deposits.

TABLE 1. POTENTIAL APPLICATION OF TREATMENT METHODS TO WASTE CONTAMINANTS

Chemical Class	Treatment Technology		
	Biodegradation*	Base-Catalyzed Hydrolysis**	Oxidation***
Aliphatic Hydrocarbons	+	-	+
Alkyl Halides	+	-	?
Ethers	+	-	?
Halogenated Ethers and Epoxides	+	+	?
Alcohols	+	-	+
Glycols/Epoxides	+	-/+	+
Aldehydes, Ketones	+	-	+
Carboxylic Acids	+	-	+
Amides	+	+	+
Esters	+	+	?
Nitriles	+	?	+
Amines	+	?	+
Azo Compounds, Hydrazine Derivatives	+	-	+
Nitrosamines	+	-	+
Thiols	+	-	+
Sulfides, Disulfides	+	-	+
Sulfonic Acids, Sulfoxides	+	?	?
Benzene & Substituted Benzene	+	-	+
Halogenated Aromatic Compounds	+	-	?
Aromatic Nitro Compounds	+	-	+
Phenols	+	-	+
Halogenated Phenolic Compounds	+	-	+
Nitrophenolic Compounds	+	-	+
Fused Polycyclic Hydrocarbons	+	-	+
Fused Non-Aromatic Polycyclics	+	-	+
Heterocyclic Nitrogen Compounds	+	-	+
Heterocyclic Oxygen Compounds	+	-	+
Heterocyclic Sulfur Compounds	+	-	?
Organophosphorus Compounds	+	-	?
Carbamates	+	+	?
Pesticides	+	+	?

(Continued)

TABLE 1. POTENTIAL APPLICATION OF TREATMENT METHODS TO WASTE CONTAMINANTS (Cont'd)

Chemical Class	Treatment Technology	
	Water Flushing#	Surfactant Flushing##
Aliphatic Hydrocarbons	-	+
Alkyl Halides	-	?
Ethers	-	?
Halogenated Ethers and Epoxides	?	?
Alcohols	+	?
Glycols/Epoxides	?	?
Aldehydes, Ketones	+?	?
Carboxylic Acids	?	?
Amides	?	?
Esters	?	?
Nitriles	?	?
Amines	+?	?
Azo Compounds, Hydrazine Derivatives	?	?
Nitrosamines	?	?
Thiols	?	?
Sulfides, Disulfides	?	?
Sulfonic Acids, Sulfoxides	?	?
Benzene & Substituted Benzene	-	+
Halogenated Aromatic Compounds	-	?
Aromatic Nitro Compounds	?	?
Phenols	+	?
Halogenated Phenolic Compounds	?	?
Nitrophenolic Compounds	?	?
Fused Polycyclic Hydrocarbons	-	?
Fused Non-Aromatic Polycyclics	-	?
Heterocyclic Nitrogen Compounds	-	?
Heterocyclic Oxygen Compounds	-	?
Heterocyclic Sulfur Compounds	-	?
Organophosphorus Compounds	?	?
Carbamates	?	?
Pesticides	?	?

(Continued)

TABLE 1. POTENTIAL APPLICATION OF TREATMENT METHODS TO WASTE CONTAMINANTS (Cont'd)

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* Potential application of biodegradation as treatment technology based upon literature identifying microbial degradation of representative compounds in class.

** Potential application of base-catalyzed hydrolysis as a treatment technology based upon calculated half-lives for hydrolysis of representative compounds at pH 9 to 11.

*** Potential application of oxidation as a treatment method based upon literature for oxidation of chemicals in water and wastewater by hydrogen peroxide.

Potential application of water flushing based upon aqueous solubility and octanol/water partition coefficient (Kow) of representative compounds. Specific application will depend on solubility and Kow for specific compounds.

Potential application of surfactant flushing based upon literature for enhanced oil and gasoline recovery.

Hypochlorite reacts with organic compounds as a chlorinating agent as well as an oxidizing agent, and demonstrations of the effectiveness of hypochlorite as an oxidizing agent for organic materials are extremely limited (7,8,9).

Hypochlorite additions to waste deposits may lead to production of undesirable chlorinated by-products (e.g., chloroform) rather than oxidative degradation products of waste contaminants, therefore its use is not recommended.

While ozone is an effective oxidizing agent for many organic compounds in wastewater treatment applications, its relatively low stability in aqueous systems, particularly in the presence of certain chemical contaminants, may preclude its effective application to waste deposits. The half-life of ozone in distilled water is less than one-half hour (10). Considering that flow rates of water through waste deposits are likely to be on the order of inches/hour or less, and that ozone's half-life in a waste deposit should be much shorter than that in distilled water, it is unlikely that effective oxidant doses of ozone can be delivered outside of the immediate vicinity of the point of application (eg, within inches or feet of an injection point). For this reason, successful use of ozone is unlikely.

Hydrogen peroxide is a weaker oxidizing agent than ozone, however, its stability in water is considerably greater. Since decomposition of hydrogen peroxide to oxygen may be catalyzed by iron or certain other metals, effective delivery of hydrogen peroxide throughout an entire waste deposit may be difficult or impossible because of the relatively low transport velocities achievable in waste deposits. Prior to consideration of hydrogen peroxide as an in situ treatment method, it will be necessary to investigate the stability (or rate of decomposition) of hydrogen peroxide in a specific waste deposit matrix.

If the effectiveness of hydrogen peroxide as an oxidizing agent for a waste treatment can be demonstrated, its application to a waste deposit does not appear to present significant problems with respect to equipment selection. The potential hazard of violent reactions of certain organic materials with hydrogen peroxide should, however, be recognized. Since addition of hydrogen peroxide solutions to a waste deposit could result in flushing of contaminants, recovery methods as well as delivery methods should be included in system design.

Application of Flushing Methods to Waste Deposits

Potential removal of contaminants from waste deposits by flushing was considered. (Classes of chemicals potentially amenable to accelerated flushing are indicated in Table 1.) Due to the complexity of possible interactions of chemical contaminants, waste deposit matrix and flushing solution (eg, surfactant type and concentration), the effectiveness of flushing to accelerate removal of contaminants from a waste deposit can be accurately estimated only through site specific laboratory simulations. At the present time, a rational basis for application of surfactant flushing methods is available only for recovery of oils (11,12,13). Flushing with water or recycled leachate alone may be effective for organic wastes demonstrated to be readily leached from waste materials in laboratory studies.

Delivery/Recovery Systems

The selection of the most appropriate delivery/recovery methods and systems requires a thorough understanding of the waste deposit site characteristics. The site must be defined with respect to the configuration of the waste deposit (areal extent and vertical depth), hydrologic characteristics (surface and subsurface) of the waste deposit, and surface and subsurface geohydrologic characteristics of the materials surrounding the waste deposit.

Delivery Methods

The matrix for delivery methods is presented in Table 2. The table shows the forced delivery method is applicable for all conditions. The choice of a gravity delivery method is more dependent on the listed parameters. The listed parameters are those that indicate differences in site characteristics that would warrant selection of one delivery method(s) over the others. The reason for selecting these parameters are briefly discussed here.

o Average Permeability of the Waste Deposit

Permeability will dictate the flow characteristics of the deposit. If the permeability of the deposit is high, then low net pressure and short time durations would be required for a solution to pass through the deposit. Low permeability means the deposit is not easily drainable and would require higher pressure and longer time duration for a solution to move through the deposit. Naturally, gravity methods are most effective for highly permeable waste deposits.

o Depth to Bottom of the Waste Deposit

This parameter is chosen based on engineering judgement. If the depth is too great then it will take a much longer time for a solution to travel through the deposit. Based on this condition, a reasonable cut-off point for a gravity delivery method is 5 meters (15 feet).

o Waste Deposit Topped by Impermeable Layer

For the forced delivery method this parameter has no bearing, although for gravity delivery methods it will have a significant impact. For example, flooding and spraying cannot be utilized as delivery methods if the surface of the deposit is topped by an impermeable layer of soil or synthetic material.

o Topography

Topographic consideration will limit, in part, the extent of applicability of gravity flow methods. For example, on a steep slope flooding or ponding delivery methods cannot be utilized. However, topography will not affect the forced delivery method(s).

o Infiltration Rate

Gravity delivery at the deposit surface is most effective for deposits deposits with high infiltration rates. Infiltration rate has no bearing in forced delivery systems.

In general, gravity delivery methods are effective when the waste deposit is situated in unsaturated zone with shallow permeable overburden and depth to bottom of the deposit is limited to 15 feet with permeability greater than 10^{-3} cm/sec.

For waste deposits covered by thick overburdens of significant depth (more than 5 meters) the forced delivery method will be most effective. For waste deposits having a permeability lower than 10^{-4} cm/sec a forced method utilizing electroosmosis could be employed for solution injection into the deposit. In general, the forced method should be highly effective for waste deposits within a permeability range of 10^{-1} cm/sec to 10^{-4} cm/sec.

Recovery Methods

Table 3 indicates the applicability of various recovery methods for different site characteristics. Only two parameters, depth to recovery zone and composite permeability are considered in the matrix. Although other parameters such as transmissivity and storativity may play an important role in designing well or wellpoint systems. These two parameters are the most appropriate guide for the preliminary selection of recovery methods. It should be noted that the recovery of injected solution will be from the saturated zone (water

TABLE 2. MATRIX FOR DELIVERY METHODS

Delivery Methods	Location of the deposit in relation to existing groundwater table		Contamination starts at		Waste deposit topped by layer of impervious material having a thickness			Topography		
	Unsaturated	Saturated	Sur-face	Sub-surface	0'	5'	Above 5'	Flat	0-3%	3%
GRAVITY										
1. Flooding	X	NA	X	X	X	NA	NA	X	X	NA
2. Ponding	X	LE	X	X	X	X	NA	X	X	NA
3. Surface Spraying	X	NA	X	X	X	NA	NA	X	X	X
4. Ditches	X	NA	NA	X	X	X	NA	X	X	X
5. Infiltration Galleries	X	NA	NA	X	X	X	X	X	X	X
6. Infiltration Bed	X	NA	NA	X	X	X	X	X	X	NA
FORCED										
1. Injejction Pipes	X	X	X	X	X	X	X	X	X	X

(Continued)

TABLE 2. MATRIX FOR DELIVERY METHODS (Cont'd)

Delivery Methods	Infiltration Rate			Hydraulic Conductivity			Depth to Bottom of the Waste Deposit		
	0.3-0.5 in/hr	0.15-0.3 in/hr	Below 0.15 in/hr	10^{-1}-10^{-3} cm/sec	10^{-3}-10^{-4} cm/sec	10^{-4}-10^{-7} cm/sec	15'	15'-40'	40'
GRAVITY									
1. Flooding	X	X	NA	LE	NA	NA	X	LE	NA
2. Ponding	X	X	LE	X	LE	NA	X	LE	NA
3. Surface Spraying	X	X	NA	LE	NA	NA	X	LE	NA
4. Ditches	X	X	X	X	LE	NA	X	LE	NA
5. Infiltration Galleries	X	X	X	NA	NA	NA	X	X	NA
6. Infiltration Bed	X	X	X	NA	NA	NA	X	X	NA
FORCED									
1. Injection Pipes	X	X	X	X	X	$X^{\#}$	X	X	X

X = Applicable

LE = Less Effective

NA = Not Applicable

$X^{\#}$ = Applicable with electro-osmosis

TABLE 3. MATRIX FOR RECOVERY METHODS

Recovery Methods	Depth To Recovery Zone			Hydraulic Conductivity			
	0-15'	15-40'	40'	10^{-1} cm/sec	10^{-1} to 10^{-3} cm/sec	10^{-3} to 10^{-4} cm/sec	10^{-5} to 10^{-7} cm/sec
GRAVITY							
Open Ditches & Trenches	X	NA	NA	X	X	NA	NA
Porous Drains	X	NA	NA	X	X	NA	NA
FORCED							
Wellpoint	X	X	NA	X	X	NA	NA
Deep Well	NA	X	X	X	X	NA	NA
Vacuum Well Point	X	X	NA	NA	NA	X	NA
Electro-osmosis	X	X	X	NA	NA	NA	X

table aquifer) and normally the recovery method(s) will be installed beyond the boundary of the waste deposit. However, when a recovery method will be installed within the waste deposit, the composite permeability of the waste deposit should be considered in selecting the recovery method. The parameter, depth to recovery zone, is chosen because gravity methods are impractical beyond a 5 meter depth and vacuum well point is also effective to a 5 meter depth. The permeability will dictate the drainage characteristics and thereby control the selection of recovery (dewatering) methods.

In general, gravity recovery methods are suitable for a shallow recovery zone (depth to water table from the surface should not be more than 5 meters). For a deeper recovery zone, forced recovery methods must be employed.

Application of Delivery/Recovery Methods to Waste Deposits

Before final selection of delivery/recovery methods, the following steps must be undertaken for each site:

Initial Site Evaluation - In this phase topographical survey and preliminary geotechnical investigations are performed. Based on these investigations the following information is obtained for each site:

- Extent and nature of the waste pile;
- Site soil characteristics such as porosity and permeability, and uniformity;
- Surface drainage characteristics of the site;
- Groundwater table location and groundwater flow direction and velocity;
- Field permeability testing of the waste deposit and host materials;
- Surface infiltration rate determination;
- Soil, waste deposit and groundwater samples collection for laboratory analyses.

Laboratory Tests - Two types of testing must be performed: chemical analysis to provide information on the nature and extent of contamination and geotechnical soil tests to provide information on the gradation and permeabilities of waste deposit and host materials.

Identification of Feasible Methods - Based on the field investigations and laboratory testings, feasible treatment and delivery/recovery methods commensurate with the treatment requirements, are identified using the matrices in Tables 1 through 3. These feasible methods are carefully evaluated based on engineering judgement to narrow down the choices for the field demonstration program.

Bench Scale Tests - Bench scale tests may be necessary to demonstrate the effectiveness of a given treatment method for a specific combination of chemical contaminant and waste deposit matrix.

Field Demonstration Program - A field demonstration program for the selected feasible methods is undertaken to evaluate the effectiveness of the methods and to generate design information, such as ditch spacing and well spacing required for proper delivery and recovery of the treatment agent.

Design and Economic Evaluation of the Effective Methods - Based on the field demonstration program, alternate delivery/recovery systems are developed and a cost evaluation is performed. Based on cost and effectiveness analysis, final selection of a delivery/ /recovery system was made for subsequent implementation.

CONCLUSIONS

To accelerate stabilization of waste piles or deposits using a combination of chemical or biological reagents and delivery/recovery systems involving gravity or forced methods of injection, a great deal more information based upon specific field experimentation must be assembled. Envirosphere has provided its judgement on what generally appears to be promising: biological stabilization, hydrolysis and flushing (combined with recovery and surface treatment/disposal), however, there is no basis for a recommendation of full scale implementation at a remedial action site. We believe that a pilot program is probably a necessary prerequisite at any site where application of in situ methods are deemed as a realistic option. Of course, how can one determine if in situ methods are realistic? The answer is: if someone, somewhere else has done it successfully before, then it would be a realistic option if it is also cost competitive with isolation and/or removal oriented alternatives. This type of feasibility question becomes so site specific as to virtually rule out a generic approach, especially given the absence of hard data on effectiveness of in situ treatment methods. To pursue this as a technical question, the future activities needed are obvious: Development and specification of pilot plant and laboratory bench scale studies to focus on the central question of the effectivness of the treatment.

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PERMEABILITY OF COMPACTED SOILS TO SOLVENTS MIXTURES AND PETROLEUM PRODUCTS

K. W. Brown, J. C. Thomas and J. W. Green
Texas Agricultural Experiment Station
Soil and Crop Sciences Department
College Station, Texas 77843
EPA Grant No. CR-808824020

ABSTRACT

The investigation of the impact of organic solvents and solvent wastes on soil permeability are continuing. Permeabilities, higher by several orders of magnitude than those measured with water, have now been observed with pure solvent chemicals, binary mixtures of pure solvents, commerical petroleum products, and solvent rich industrial wastes in fixed wall compaction mold permeameters in the laboratory and with solvent rich industrial wastes in field cells.

The higher permeabilities observed in the laboratory occurred irrespective of the hydraulic gradients applied. The higher permeability to polar organic liquids diminishes as the organics are diluted with water, such that mixtures of over 50% water behave like water. Soils were also more permeable to other organic liquids in common use, including gasoline, kerosene, diesel oil, and paraffin oil. Permeabilities to these liquids are similar to those found with organic solvents. Two soils admixed with commercially available clays commonly used for abatement of industrial wastes also demonstrated higher permeabilities to organic liquids than to water.

INTRODUCTION

Field and laboratory studies determining the impact of organic chemicals on the permeability of soil liners have previously been reported (Brown and Anderson, 1980; Anderson and Brown, 1982; Brown _et al_., 1983). These reports dealt with the following: a literature review of possible mechanisms through which chemicals impact compacted soil liners; presentation of laboratory permeameter data using pure chemicals on four native clay soils; and the permeability to organic wastes of three additional compacted soils containing different predominant clay minerals, in the laboratory and in field cells.

Concentrated pure organic solvents and organic-rich solvent wastes are indicated to cause soil permeabilities two or three orders of magnitude higher than those determined with water (0.01 N $CaSO_4$ solution). These differences cannot be explained by the differences in viscosity and density between the organic solvents and water. Much higher permeabilities to polar organics have been observed, particularly after as little as 0.2 pore volumes of liquid have been displaced. These higher permeabilities coupled with the observed dye patterns, indicated that the organics are moving through preferential channels. The channels are probably a result of chemicals displacing water and dessicating the clays, thus causing them to shrink and crack.

The materials used in the laboratory and field, plus methods employed, have previously been reported. Additional data gained from field cells which were disassembled since the previous report (Brown et al., 1983) are presented briefly. This report will emphasize laboratory studies of: 1) the effects of elevated hydraulic gradient; 2) influence of dilutions of polar compounds with water; 3) influence of mixtures of polar and nonpolar compounds; 4) the influence of gasoline, kerosene, diesel oil, and paraffin oil on the permeability of compacted soils; and 5) the impact of organic liquids on two commercially available clay admixes.

MATERIALS AND METHODS

Soil

The soils used in the studies of hydraulic gradient, solvent dilutions, and petroleum product permeation included three blends selected to represent the range of available materials widely used for the construction of land disposal facility clay liners. A sand was mixed with either of three clays obtained from geologic deposits, e.g., kaolinite, mica, or bentonite to achieve water permeabilities in the range of 1 x 10^{-8} to 1 x 10^{-9} cm/sec. In the following disscusion, the soils are referred to by their dominant clay mineralogies, viz. kaolinite, mica, or bentonite. These are the same soil blends used in earlier studies (Brown et al., 1983).

Laboratory Testing Procedure

Soils were compacted in fixed wall permeameters as described in previous reports by Anderson et al. (1982) and Brown and Anderson (1983). Hydraulic conductivity was measured after compaction to at least 90% proctor density at moisture content slightly wet of optimum. Permeability tests with water (0.01 N $CaSO_4$) were conducted on replicate samples. The effects of pressure on permeability were tested with both wastes on laboratory compacted soils that had been saturated first with 0.01 N $CaSO_4$ and on unsaturated soils at the moisture content used for compaction. Pressures of 5, 15, and 30 psi equivalent to hydraulic gradients of 31, 91, and 181 were tested on the kaolinitic and micaceous soils. Bentonitic soils were tested at 15, 30, and 45 psi, equivalent to hydraulic gradients of 91, 181, and 272. Samples tested with water were permeated until approximately 1 pore volume of water had penetrated the sample. The liquid chamber was then opened, waste was substituted for the water, and pressure was reapplied. Samples of effluent were collected, quantified, and subsampled for analysis. Collection continued until the permeability data indicated no further increase or until the permeability exceeded 1 x 10^{-4} cm/sec.

To measure the effect of diluting a polar organic solvent with water, the permeability of an unsaturated micaceous, compacted soil was measured. Mixtures consisting of 0:100, 2:98, 12.5:87.5, 25:75, 50:50, 75:25, and 100:0 (acetone:water, % by volume) were applied to separate soil samples in triplicate at a hydraulic gradient of 91.

Small samples of the clays were treated with acetone, xylene and dilution of acetone and examined by x-ray diffraction to investigate the effect of the liquids on d-spacing. The clays were equilibrated with saturated water vapor pressure in an environmental controlled chamber similar to that used by Rhoades et al. (1979). Acetone or xylene was added dropwise, and periodic diffraction patterns were run until no further change in d-spacing was detected. The initial values were taken after several drops of acetone had been allowed to equilibrate with the clay in the specimen holder.

To determine the effects of other organic liquids on compacted soils, three replications of non-saturated micaceous soil were exposed to diesel fuel, kerosene, gasoline, motor oil, and paraffin oil at a gradient of 91. Properties of the liquids tested are given in Table 1.

Two commercially available clays, sold specifically for use as soil amendments to decrease the permeability of soil liners in landfills or surface impoundments, were mixed with sand to achieve a permeability to water of about 1×10^{-8} cm/sec. The permeant liquids, water, xylene, acetone, kerosene, diesel fuel, gasoline, and motor oil, are being tested at a hydraulic gradient of 91. The clays, CC1 and CC2, have been characterized as shown in Tables 2 and 3.

RESULTS AND DISCUSSION

Field Cells

These studies are still in progress. Results from 12 of the 27 test cells were reported earlier (Brown et al., 1983). Since that time, six additional cells have been taken apart and the soils examined. Table 4 summarizes the data from these six cells. A comparison of data obtained from laboratory and field studies of the same soils is presented in Table 5. Since not all replications of all treatments applied in the field cells have been excavated and the soils examined, no conclusions will be presented. The un-excavated soils primarily represent kaolinite and mica soils permeated with acetone waste. All but one liner is now leaking waste. The permeability of the liners have not yet stabilized at a value where cell examination is considered relevant.

Table 1. Physical and Chemical Properties of Five Organic Fluids[1].

Liquid	Viscosity (Centistokes)	Density g/cm^3	Surface Tension dynes/cm @ 85°C
Paraffin Oil	75	0.93	28.8-48
Diesel Oil[2]	1.4-2.5	0.87	
Gasoline[2]	0.69	0.70-0.75	24.4-25.8
Motor Oil SAE 30[2]	8.8-13	0.81-0.90	36.0-37.5
Kerosene[2]	0.7-0.9	0.79-0.82	30.7-31.2

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2. Commercial product obtained locally.

Table 2. Physical and Chemical Characteristics of the Commercial Clays Evaluated Here.

Parameter	CC1	CC2
pH	8.5-9.5	8.5-10.0
CEC meq/100g*	95-130	80
Al_2O_3 (%)	18-22	21.08
CaO (%)	0.62	0.65
Fe_2O_3 (%)	3.0	3.25
MgO (%)	2-2.5	2.67
Na_2O (%)	2-2.5	2.57
SiO_2 (%)	60-63	63.02
Mineralogy	blue bentonite	bentonite synthetically treated
Particle size (dispersed in water)		
<44 micron %		96
<5 micron %		93-94
<0.5 micron %		87-89
<0.1 micron %		60-65

*Measured by methylene blue titration technique.

Table 3. Particle Size Distribution for Commercial Clays After Mixing with Sandy Loam to Obtain Desired Permeability to Water.

	CC1	CC2
% sand	89.6	84
% silt	0.4	5.5
% clay	10	10.5
Sand fraction		
>2.0 mm	0	0
1-2 mm	0.1	0
0.5-1 mm	0.1	0.1
0.25-0.5 mm	20.3	5.4
0.106-0.25 mm	68.1	77.9
<0.106 mm	1.0	0.6

Table 4. Test Cells Disassembled Since Those Reported on in Brown et al. (1983).

Dominant Clay Mineralogy in soil liner*	Waste Type	Initial K	Final K
Bentonite (Replication 2)	Xylene Paint	1.7×10^{-8}	1.1×10^{-7}
Bentonite (Replication 3)	Xylene Paint	0**	0
Bentonite (Replication 4)	Acetone	0**	0
Mica (Replication 1)	Acetone	1.8×10^{-8}	1.2×10^{-7}
Mica (Replication 2)	Acetone	3×10^{-10}	4.1×10^{-8}
Mica (Replication 3)	Acetone	1.4×10^{-8}	7.7×10^{-8}

* Commercial clays admixed to a sandy loam soil, wetted to optimum moisture, compacted to near Standard Proctor.

** No leachate was collected on these test cells between installation and removal for inspection.

Table 5. Conductivity of Three Compacted Soil Liners to Water Measured in the Laboratory at a Hydraulic Gradient of 91, Pure Xylene and Acetone Measured in the Laboratory Using Non-Saturated Soil and a Gradient of 91, Waste Xylene and Acetone Measured in the Laboratory Using Non-Saturated Soil and a Gradient of 91, and Waste Xylene and Acetone Waste Measured in Field Test Cells Using Non-Saturated Soils and a Gradient of 7.

Dominant Clay in Compacted Soils	Water ($0.01N\ CaSO_4$) in Lab	Pure Xylene in Lab	Waste Xylene in Lab	Waste Xylene in Field	Pure Acetone in Lab	Waste Acetone in Lab	Waste Acetone in Field
Kaolinite	5.5×10^{-9}	7.3×10^{-5}	2.2×10^{-6}	1×10^{-6}	5×10^{-7}	3.0×10^{-7}	1×10^{-6}
Mica	1.0×10^{-8}	4.1×10^{-5}	1.8×10^{-6}	2×10^{-6}	6.7×10^{-7}	1.1×10^{-7}	1×10^{-7}
Bentonite	5×10^{-9}	6×10^{-5}	1.2×10^{-8}	1×10^{-7}	*	*	*

* Tests in progress.

The six cells examined since last year have demonstrated essentially the same characteristics of solvent movement through fracture openings as did the earlier cells. The bentonitic soil, where the waste had not completely penetrated through the total soil depth (e.g. rep. 3, xylene waste), demonstrated a striking visual and odiferous wetting front marked by sulfides and black color. Reducing conditions associated with corroding iron drums and bacterial action are presumed to cause this phenomena. Complete analysis of all the data from the field tests will be provided when all cells have been examined in detail. The difference in hydraulic gradient (7) present in the field cells from that used in laboratory permeability studies of the same soils (181) has contributed to the long time required for the waste to penetrate the liners.

Laboratory Results

Effects of Pressure

While Darcian flow should be independent of the hydraulic gradients we are using, the elevated pressures could possibly have some impact system because of the presence of the organic liquids. It is common technique in most laboratories to allow a conductivity test cell, loaded with a soil sample, to set undisturbed overnight, or some other arbitrary period of 12 to 24 hours, with the permeant liquid in contact with the soil at ambient temperature and atmospheric pressure. Experience with these testing technicians has demonstrated that if elevated pressures are applied immediately after sample preparation and cell loading, rather than slowly increased over some time period, there is a greater tendency for the permeant liquid to flow through the sample chamber quickly, simulating rapid breakthrough and untrustworthy results. Dye tracer studies conducted in our laboratory indicated that such early and premature breakthrough was a result of sidewall flow. Therefore, these studies of varying hydraulic gradient were preceded by a 24-hour "aging" or "curing" period before the pressure was imposed on the permeant liquid within the permeability test apparatus.

The average permeability of the three soils to water at three pressures is shown in Table 6. There is a tendency for the permeabilities to increase slightly with hydraulic gradient, particularly on the bentonitic soil; however, the differences do not appear to be statistically significant. The available data for the effects of elevated pressures on the permeability of presaturated and unsaturated soils to acetone and xylene are given in Table 7. While the data set is not yet complete, the final permeability to the organic liquid will apparently be much greater than that to water in all cases. The permeability of micaceous soil to acetone decreased with increased pressure and increased with increasing pressure when tested with xylene. The variability is such, however, that the trends noted are not likely to be significant.

The comparison of permeability increases at hydraulic gradients of 7 or less used in the field (Table 5) with these results further indicates that the values measured with organic liquids are greater than those measured with water and are independent of the pressure applied.

Dilutions of Acetone

Compacted micaceous soil was tested at a hydraulic gradient of 91 with 100, 75, 50, 25, 12.5, and 2% acetone diluted with water on replicate samples. Hydraulic conductivities of laboratory grade acetone through micaceous soil for both the non-saturated and presaturated states were reported in

Table 6. Average Permeability of Three Soils to Water at Various Hydraulic Gradients.

Soil	Hydraulic Gradient			
	31	91	181	272
Kaolinite	1.18×10^{-8}	1.18×10^{-8}	1.02×10^{-8}	*
Mica	1.55×10^{-8}	1.4×10^{-8}	9.2×10^{-9}	*
Bentonite	*	7.5×10^{-10}	3.92×10^{-9}	3.2×10^{-9}

* Not run.

Table 7. Average Permeability of Compacted Soil Liners to Acetone and Xylene at Four Hydraulic Gradients Under Both Presaturated and Nonsaturated Conditions.

	Presaturated Gradient				Nonsaturated Gradient			
	31	91	181	272	31	91	181	272
Acetone								
Kaolinite	4.4×10^{-5}	6.0×10^{-7}	1.1×10^{-6}	*	1.0×10^{-6}	1.0×10^{-6}	6.8×10^{-6}	*
Mica	1.0×10^{-6}	3.5×10^{-7}	1.5×10^{-8}	*	1.4×10^{-6}	5.4×10^{-7}	6.0×10^{-8}	*
Bentonite	*	2.2×10^{-9}	5.2×10^{-9}	2.6×10^{-8}	*	**	**	2.2×10^{-7}
Xylene								
Kaolinite	1.7×10^{-6}	8.0×10^{-6}	Incomplete	*	1.5×10^{-6}	1.4×10^{-6}	1.5×10^{-4}	*
Mica	2.8×10^{-6}	3.0×10^{-6}	2.0×10^{-5}	*	3.3×10^{-7}	1.2×10^{-4}	2.8×10^{-5}	*
Bentonite	*	4.0×10^{-7}	**	6.0×10^{-7}	7.0×10^{-5}	6.0×10^{-5}	1.4×10^{-4}	*

* Not run.

** Data not yet complete.

Brown *et* *al*. (1983). These data were used as the 100% acetone values for the purpose of comparison in this study.

Representative data are shown in Figures 1 through 6. As can be seen by comparing Figures 6 and 1 through 5, the increase in hydraulic conductivity over that measured with water increases as the concentration of acetone is increased.

An increase in hydraulic conductivity was measured on all permeameters where the concentration of acetone was 75% or greater. The lower concentrations (12.5 and 25% acetone) apparently have a lower hydraulic conductivity than was found with water. One possible explanation for the observed data is that low concentrations of acetone may cause dispersion and swelling while high concentrations may result in flocculation and shrinkage. In addition, there may be an interaction between low concentrations of acetone and the water layers on mineral surfaces resulting in an alignment of the carbonyl group towards the mineral surface and the methyl groups (hydrophobic in nature) towards the pore wall (Parfitt and Mortland, 1968). This alignment could result in a decrease in effective pore diameter at low concentration of acetone.

Mixtures of Acetone and Xylene

A summary of the effect of mixtures of acetone and xylene on the permeability of the micaceous soil liners compacted in the laboratory permeameters at a hydraulic gradient of 91 is shown on Figure 7. At 100% xylene, the permeability (non-saturated soil) is four orders of magnitude greater than the value found with water. When acetone is added to the xylene, i.e. 12.5% acetone to 87.5% xylene, the permeability is dramatically reduced, i.e. 3.3 orders of magnitude lower than with xylene alone as a permeant, but is still greater than for water. As the concentration of acetone is increased in the xylene:acetone mixture, the hydraulic conductivity remains low until the concentration of acetone is greater than 50%. At concentrations of 75 to 100% acetone, the permeability reached a plateau at about 1.5 orders of magnitude greater than the

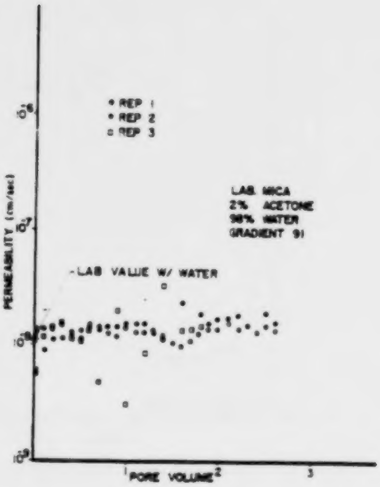

Figure 1. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil, permeated with 2% acetone and 98% water mixture, at the "as compacted" moisture content and a hydraulic gradient of 91.

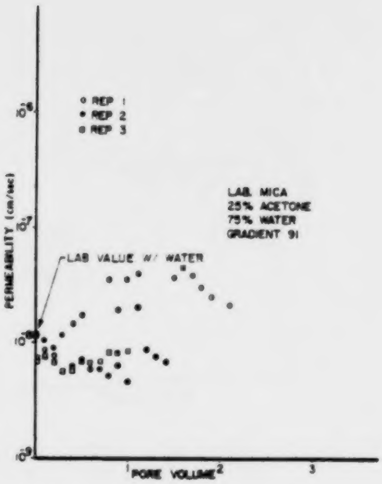

Figure 3. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil, permeated with 25% acetone and 75% water mixture, at the "as compacted" moisture content and a hydraulic gradient of 91.

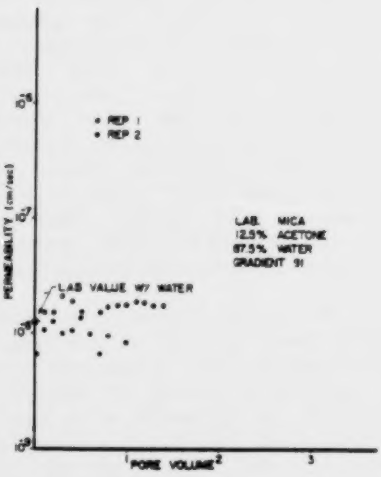

Figure 2. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil, permeated with 12.5% acetone and 87.5% water mixture, at the "as compacted" moisture content and a hydraulic gradient of 91.

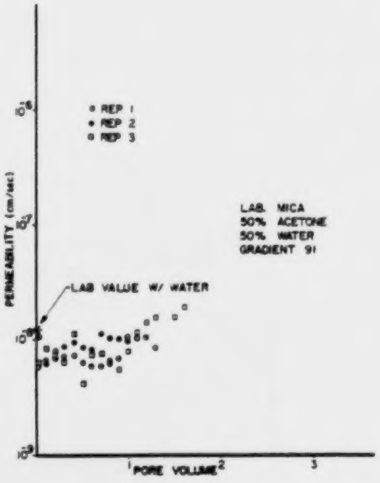

Figure 4. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil, per meated with 50% acetone and 50% water mixture, at the "as compacted" moisture content and a hydraulic gradient of 91.

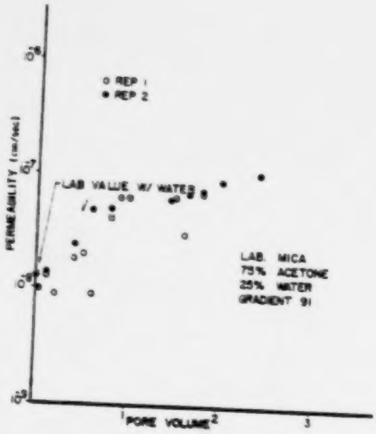

Figure 5. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil, permeated with 75% acetone and 25% water mixture, at the "as compacted" moisture content and a hydraulic gradient of 91.

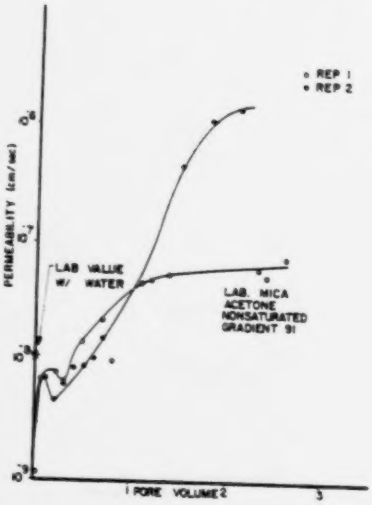

Figure 6. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil, permeated with acetone at the "as compacted" moisture content and a hydraulic gradient of 91.

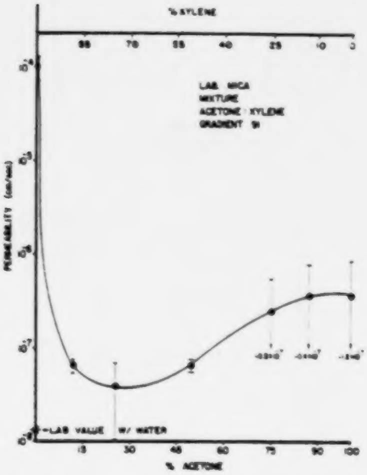

Figure 7. Hydraulic conductivity versus percent acetone and percent xylene of micaceous soil permeated by various mixtures of acetone and xylene at the "as compacted" mixture content and a hydraulic gradient of 91.

permeability to water.

One possible explanation of this phenomena is that the concentrated solvents have a greater impact on the shrinkage of the clay than the mixtures of the chemicals. The collapsing of the clay platelets, particularly along pore walls, could cause an effective pore diameter greater than that found in the water permeated soil liner. This increase in pore diameter could result in an increase in hydraulic conductivity.

The x-ray diffraction investigations found an initial swelling of the d-spacing of the bentonitic clay from 34 to 36 Å (Table 8) with acetone, which is in agreement with the initial decrease in hydraulic conductivity as reported by Brown _et_ _al_. (1983). The subsequent decrease in d-spacing to 12 Å as more acetone was added could account for the observed increase in permeability as the clay shrinks in response to decreases in interlayer spacing. The decrease in d-spacing found in the same clay material with high xylene concentra-

Table 8. D-spacings (Å) Found for Selected Clay Materials Eluted With Acetone Or Xylene Under Saturation Water Vapor Pressure.

Clay Material	Solvent	D-spacing
Bentonite	Water	34
	Glycerol	18
	Acetone (i)	36
	(f)	12.6
	Xylene (i)	27
	(f)	18.4
Mica	Water	10
	Acetone	10
	Xylene	10
Kaolinite	Water	7.12
	Acetone	7.12
	Xylene	7.12

i = after a few drops were added.
f = after a plateau reached.

tions coincides with the increase in permeability exhibited by the bulk soils. The constant d-spacing for the other clay materials was as expected, as they are non-expansive clay minerals. Changes in space between clay minerals which may be responsible for the behavior of these clays cannot be measured with this technique.

Permeability to Petroleum Products

Kerosene

The laboratory permeability of non-saturated compacted micaceous soil to kerosene is given in Figure 8. While the compacted soil had an initial permeability to water of 1 x 10^{-8}, the permeability to kerosene was slightly greater than 1 x 10^{-5} for rep 3 and about 8 x 10^{-5} for reps 1 and 2. Thus, the permeabilities of kerosene are higher than to water by 3 to 4 orders of magnitude. In all cases, one half of the difference was achieved within the first 0.1 pore volume. In two replications, the maximum permeabilities to kerosene were achieved by 0.5 pore volumes while rep. 3 did not achieve a maximum permeability until the passage of 1.75 pore volumes.

Paraffin Oil

The permeability of compacted, non-saturated micaceous soil to paraffin oil was about one order of magnitude greater than the comparable permeability to water (Figure 9). The permeability increased rather rapidly and reached a plateau or maximum value by the passage of 1 pore volume. While this change may not be as dramatic as that for some of the other organics tested, the permeability to paraffin oil is still 10 to 100 times the permeability to water.

The viscosity of paraffin oil is much greater than that of water and the other liquids tested. The greater viscosity would slow the flow of paraffin oil through the soil, and thus the permeability was not expected to be as great as that for the other liquids tested.

Diesel Fuel

The permeability of compacted non-saturated micaceous soil to diesel fuel was 1 to 1.5 orders of magnitude greater than the corresponding permeability to water (Figure 10). Since the data appeared variable, an extra replication was run. Permeability values for reps. 1 and 2 did not appear to plateau but initially rose for the first 0.75 to 1.25 pore volumes then slowly but steadily declined. Permeability of rep. 3 rose initially in the first 0.1 pore volume, decreased steadily until 1.75 pore volumes, remained constant until 3.2 pore volumes, and then rapidly increased and remained high. Again data show a permeability to diesel fuel of 10 to 100 times the permeability to water.

Gasoline

Permeability of non-saturated compacted micaceous soil to gasoline (Figure 11) was 2 orders of magnitude greater than the permeability to water. This permeability was observed

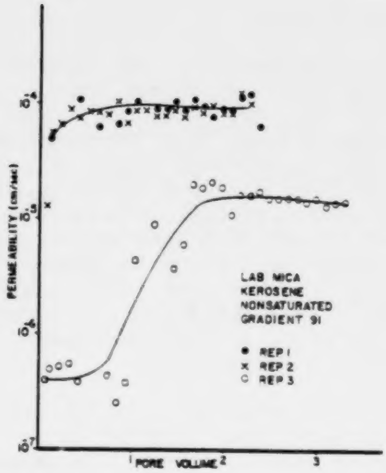

Figure 8. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil exposed to kerosene at a hydraulic gradient of 91.

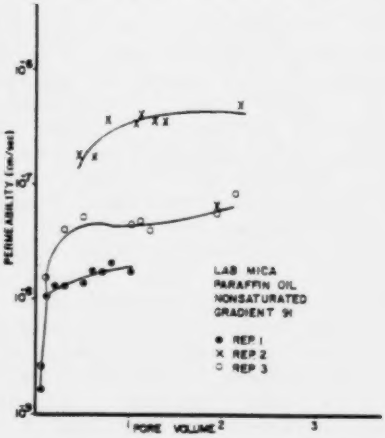

Figure 9. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil exposed to paraffin oil at a hydraulic gradient of 91.

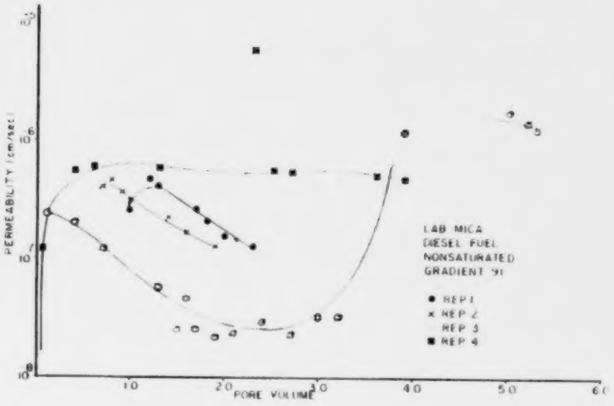

Figure 10. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil exposed to diesel fuel at a hydraulic gradient of 91.

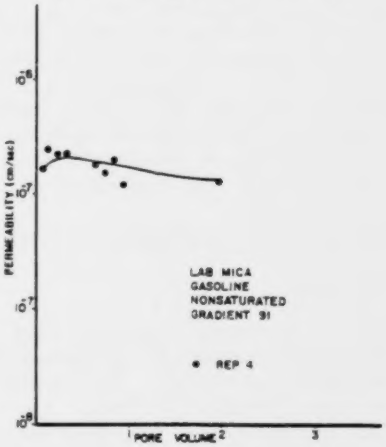

Figure 11. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil exposed to gasoline at a hydraulic gradient of 91.

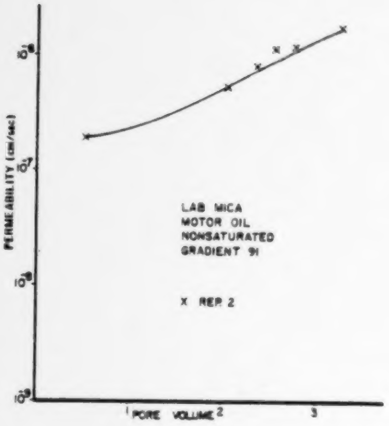

Figure 12. Hydraulic conductivity versus pore volume for laboratory compacted micaceous soil exposed to motor oil at a hydraulic gradient of 91.

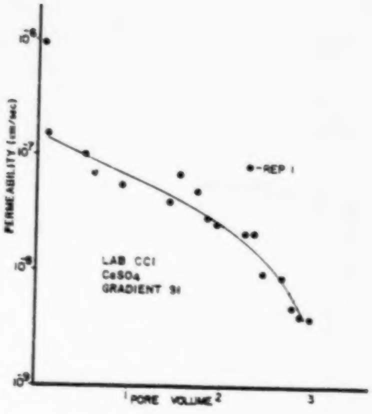

Figure 13. Hydraulic conductivity versus pore volume for laboratory compacted commercial clay 1 (CC 1) admixed soil exposed to water (.01 N $CaSO_4$) at a hydraulic gradient of 91.

within 0.1 pore volumes and remained within the range of 1 to 2 x 10^{-6} up to the passage of 1.9 pore volumes.

Motor Oil

The permeability of non-saturated compacted mica clay to motor oil (Figure 12) showed a value of 2 x 10^{-7} within the first 0.5 pore volumes. The permeability then steadily rose until reaching 1.5 x 10^{-6} cm/sec at 3 pore volumes.

Commercial Clays

The permeability of CC1 (one of the two commercially obtained clays admixed with sand) to water (.01 N $CaSO_4$) began at 1.4 x 10^{-7} cm/sec and decreased to 4 x 10^{-9} cm/sec after 2.9 pore volumes were displaced. This clay exhibited a steady decrease in permeability and did not reach a constant value even after 3 pore volumes (Figure 13). The behavior of this clay when exposed to xylene was quite different (Figure 14). Within 0.5 pore volume, the permeability rose to 1.8 x 10^{-4} and slowly increased thereafter to 2.8 x 10^{-4}. Thus, the permeability of CC1 to xylene was 3 orders of magnitude greater than the initial water permeability and 4.5 orders of magnitude greater than the lowest permeability to water measured. Permeability of CC1 to acetone (Figure 15) was similar to that of xylene. It increased within the first 0.5 pore volumes to 3 x 10^{-5} or greater and became fairly steady thereafter. Of the 2 replications studied, one equilibrated at about 9 x 10^{-5} and the other at 3.5 x 10^{-5} cm/sec. Again, this is 2.5 to 3 orders of magnitude above the permeability to water.

The permeability of CC2 (the second commercial clay admixed with sand) to water (0.01 N $CaSO_4$) was initially 7.5 x 10^{-8} and decreased to an average of about 1.8 x 10^{-8} cm/sec (Figure 16). There was a decrease and then an increase in permeability between 1.5 to 2.25 pore volumes that is unexplained at this time. Exposure of CC2 to xylene resulted in much higher permeability (Figure 17). One replication showed a permeability to xylene of 6 x 10^{-6} and the others had permeabilities of 7 x 10^{-4} and 2 x 10^{-3} cm/sec. This again represents permeabilities of

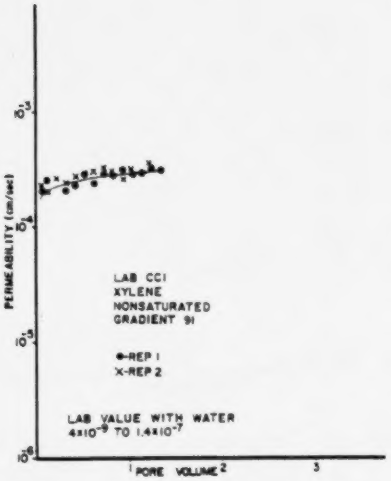

Figure 14. Hydraulic conductivity versus pore volume for laboratory compacted commercial clay 1 (CC 1) admixed soil exposed to xylene, at the "as compacted" moisture content and a hydraulic gradient of 91.

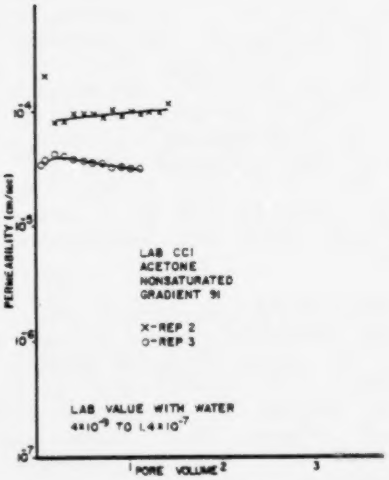

Figure 15. Hydraulic conductivity versus pore volume for laboratory compacted commercial clay 1 (CC 1) admixed soil exposed to acetone, at the "as compacted" moisture content and a hydraulic gradient of 91.

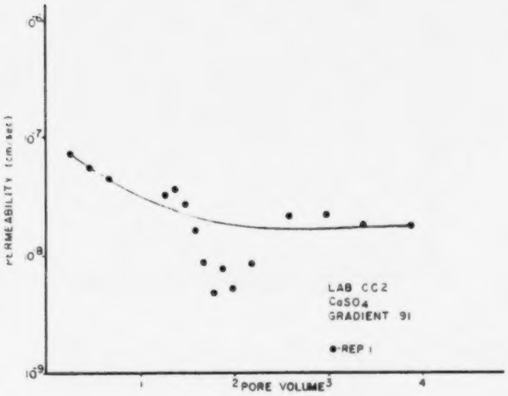

Figure 16. Hydraulic conductivity versus pore volume for laboratory compacted commercial clay 2 (CC 2) admixed soil exposed to water (.01 N $CaSO_4$) at a hydraulic gradient of 91.

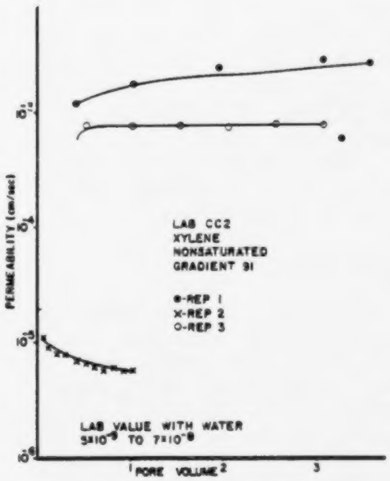

Figure 17. Hydraulic conductivity versus pore volume for laboratory compacted commercial clay 2 (CC 2) admixed soil exposed to xylene, at the "as compacted" moisture content and a hydraulic gradient of 91.

2.5, 4.5, and 5 orders of magnitude higher than the permeability to water.

In summary, both commercial clays performed similarly in laboratory tests to the other clay materials tested and reported in this and previous papers. The permeability of these two clays to water bears no resemblance to their permeabilities to pure organic liquids.

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EFFECTS OF HYDRAULIC GRADIENT AND METHOD OF TESTING ON THE HYDRAULIC CONDUCTIVITY OF COMPACTED CLAY TO WATER, METHANOL, AND HEPTANE

David E. Foreman and David E. Daniel
The University of Texas
Austin, TX 78712

ABSTRACT

Permeability tests are being performed on three compacted clays using compaction-mold permeameters, consolidation-cell permeameters and flexible-wall permeameters. Hydraulic gradients of 10, 50, 100, and 300 are being used. The permeant liquids include water, methanol, and heptane. Approximately one third of the tests are complete; the remaining tests are scheduled for completion by August, 1984.

Results of tests on one of the soils (kaolinite) and two of the liquids (water and methanol) indicate the following: 1) the hydraulic conductivity of kaolinite to water is about the same regardless of permeameter type or hydraulic gradient; 2) when flexible-wall or consolidation-cell permeameters are used at hydraulic gradients of 100 and above, kaolinite is twice as permeable to methanol as it is to water; 3) when compaction-mold permeameters are used at hydraulic gradients of 100 and above, kaolinite is 10 times more permeable to methanol than to water; and 4) hydraulic gradient has a small effect for kaolinite permeated with methanol in flexible-wall permeameters but may have an important effect in consolidation-cell or compaction-mold permeameters where the trend is for decreasing hydraulic conductivity with decreasing gradient. The effects of side-wall leakage, applied stresses, and degree of saturation are thought to be the causes of differences observed with the various types of permeameters.

INTRODUCTION AND PURPOSE

Compacted clay is widely used for lining solid waste landfills and waste storage lagoons. Several studies have been conducted in recent years to investigate the effects of organic solvents on the hydraulic conductivity (k), or permeability of compacted clay (2,3,4). Most of these studies have shown that compacted clays are more permeable to organic solvents than to water. However, nearly all the experiments were accelerated by elevating the hydraulic gradient to values well in excess of those that would be expected in the field. The question is: Are compacted clays more permeable to organic solvents than to water even at more realistic hydraulic gradients? In addition, do other test variables, such as type of permeameter, affect the hydraulic conductivity of soils to organic solvents, and if so, why?

APPROACH

Testing Program

To determine the effects that hydraulic gradient, permeant liquid, and type of permeameter have on the hydraulic conductivity of compacted clay, constant-head permeability tests are being performed on samples of compacted clay using both flexible-wall and rigid-wall permeameters. Three soils are being permeated at four hydraulic gradients with three different permeant liquids. Hydraulic gradients of 10, 50, 100, and 300 are applied, with additional intermediate gradients applied in a few circumstances. Replicate tests on different soil specimens are run. Since actual testing has addressed only a few of the total parameter combinations at the time of this writing, a complete result matrix depicting the results of over 300 planned tests would contain mostly gaps.

Soils

The soils used in this study are a noncalcareous smectitic clay, a mixed-cation illitic clay, and a commercially-processed kaolinite. The noncalcareous smectitic clay is Lufkin clay obtained from the Texas A & M campus with the help of K. W. Brown. The mixed-cation illitic clay is Hoytville clay from northwestern Ohio and was also obtained through Brown's help. Lufkin clay and Hoytville clay were used in a study by Anderson and Brown (1). The kaolinite was obtained from Georgia Kaolin Company, Elizabeth, New Jersey, and is type Hydrite R.

The three permeant liquids used in this study are water (0.01 N $CaSO_4$), laboratory solvent grade methanol, and heptane. Methanol is a neutral polar organic liquid, and heptane is a neutral nonpolar organic liquid. These three liquids were selected because they span a wide range in dielectric constant (2 to 80).

Atterberg limits of the three soils, using water (0.01 N $CaSO_4$) or methanol are presented in Table 1. Standard ASTM procedures were applied to assess these engineering characteristics.

TABLE 1. ATTERBERG LIMITS* OF SOILS TO WATER AND TO METHANOL

Soil	Water			Methanol		
	LL	PL	PI	LL	PL	PI
Lufkin Clay	56	14	42	33	N.P.	-
Hoytville Clay	48	19	29	35	29	6
Kaolinite	58	34	24	74	45	29

* LL = liquid limit; PL = plastic limit; PI = plasticity index
N.P. indicates "non plastic"
These tests were performed according to current ASTM methods, which specify reporting method and acceptable precision

Methanol reduced the liquid limits of Hoytville and Lufkin clay substantially and virtually eliminated the plasticity of these two soils. When kaolinite was tested with methanol, the liquid limit and plasticity index increased compared with water. Tests have not yet been completed for heptane.

Permeameters

Two types of permeameters are in common use: rigid-wall and flexible-wall permeameters. The flexible-wall device used for this project is shown in Fig. 1 and is described in more detail by Boynton (1). Two types of rigid-wall permeameters are used: 1) compaction-mold permeameters (Fig. 2); and 2) consolidation-cell permeameters (Fig. 3). With compaction-mold permeameters, the applied vertical stress is zero. With consolidation-cell devices, a vertical stress is applied to simulate the weight of any overlying soil or waste. With flexible-wall devices, an all-round stress of desired magnitude is applied. Backpressure saturation of 40 pounds per square inch (psi) was used with the flexible-wall permeameter. Backpressure was not used with the other devices. A nominal consolidation stress of +15 psi was used with the consolidation-cell and flexible-wall permeameters.

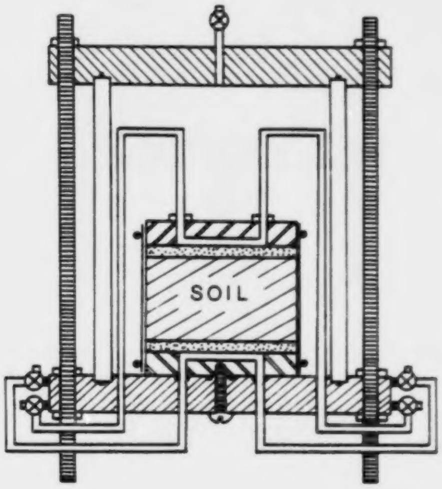

Figure 1. Flexible Wall Permeameter. The soil sample has a diameter of 4 inches (in.) and a height of 3.7 in. The drawing is not to scale.

Most of the tests for this project are being performed using flexible-wall permeameters. However, we are also conducting sufficient tests using rigid-wall and consolidation-cell equipment to permit comparison of results.

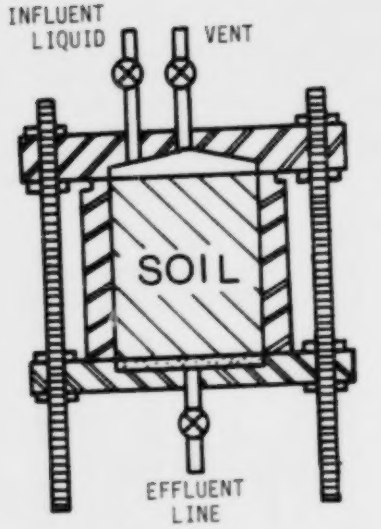

Figure 2. Compaction Mold Permeameter. The soil sample has a diameter of 4 in. and a height of 4.7 in. The drawing is not to scale.

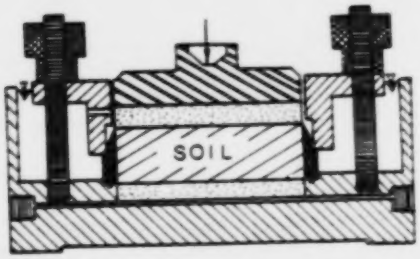

Figure 3. Consolidation Cell Permeameter. The soil sample has a diameter of 2.5 in. and a height of 0.75 in. The drawing is not to scale.

Soil Preparation

Soil samples are prepared by compacting soil mixed at or slightly dry of the optimum moisture content. The compaction is performed according to ASTM D-698. The soil is scarified between each lift (approximately 1.7 in. thick). Samples that are to be tested in a flexible-wall permeameter are extruded from the compaction mold and approximately 1 centimeter (cm) of soil is trimmed from the ends.

Procedure with Flexible-Wall Permeameter

After a sample is set-up in a flexible-wall permeameter, it is soaked with the permeant liquid for 24 to 48 hours. To soak a sample, a vacuum of 15 in. of mercury (7.4 psi) is placed on the top of the soil and the base of the soil is opened to a reservoir of permeant liquid at atmospheric pressure. Air bubbles are removed from the sample as the fluid flows upward through the sample. A 5-psi-cell pressure is used during soaking. After the soaking stage is complete, the sample is backpressured for 24 to 48 hours. Backpressuring causes nearly all the air bubbles remaining in the sample to go into solution with the soaking fluid. To backpressure a sample, the cell pressure is raised to 55 psi, and 40 psi pressures are placed on the top and bottom of the soil sample.

To permeate the sample, the pressure on the bottom of the soil is raised, and the pressure on the top of the soil is lowered to produce the desired pressure difference. The average backpressure is kept at 40 psi, and the cell pressure is kept at 55 psi. Tests at all gradients except 300 are performed at an average effective stress of 15 psi. Tests with a triaxial cell at a hydraulic gradient of 300 are performed at an average effective stress of 25 psi. This is because the headwater pressure must be raised to 60 psi and the tailwater pressure must be lowered to 20 psi to produce a hydraulic gradient of 300. To keep the membrane pressed against the soil, the cell pressure is increased to 65 psi.

Nearly all tests are performed until at least 2 pore volumes of permeant liquid have passed through the sample and the hydraulic conductivity is steady. With some tests, 3 to 4 pore volumes of flow is necessary to achieve steady conductivity.

Procedure with Consolidation-Cell Permeameter

A consolidation-cell permeameter, as shown in Figure 3, used the central portion of a 4-in.-diameter compacted soil sample, trimmed into a 2.5-in. diameter consolidation ring with a height of 0.75 in. A vertical stress of 15 psi was applied and the soil soaked. After the height of the sample ceased to change, permeant liquid was pressurized to initiate upward seepage through the soil. The rate of inflow and sample height were measured periodically.

Procedure with Compaction-Mold Permeameter

The soil is left in the original compaction mold and set up for testing as shown in Fig. 2. The permeant liquid is stored in a pressurized reservoir and flows downward through the soil. The soil is free to swell; otherwise the procedure generally follows that described by Brown and Anderson (2).

PROBLEMS ENCOUNTERED

The biggest problem encountered was finding a soil-confinement membrane for the triaxial apparatus that will resist the chemical attack of heptane. Membrane compatibility tests were conducted in beakers of methanol and heptane prior to any permeability testing. Latex membranes were immersed into beakers containing these fluids and the condition of the membranes was observed. Methanol did not harm the latex membrane in any noticeable way. Since then, dozens of permeability tests have been conducted with latex membranes and methanol with no trouble at all. The beaker test with a latex membrane immersed in heptane revealed that the membrane expanded but did not rupture. It was assumed that a latex membrane might work with heptane. A permeability test was set-up with heptane as the permeant liquid. Two days into the test, the membrane ruptured and the test was ruined.

There have been several ideas on how to create a satisfactory membrane for tests with heptane. A thick butyl rubber membrane was obtained, and it became apparent that this would not work because it would be too difficult and inconvenient to place a sample inside the bulky, stiff membrane. Another idea was to coat soil samples with a spray-on Teflon lubricant and then place the usual latex membrane around the soil. This idea did not work either.

The latest idea seems to be working. A 6-in. wide roll of Teflon tape was purchased, and a length of this tape was wrapped around the circumference of a soil sample, top cap, and base pedestal. Two to three revolutions of tape around the sample were used. Then, a regular latex membrane was placed over the Teflon tape and sealed in the usual way. The sample of soil was set up in a permeability cell, and heptane under a pressure of 40 psi was placed on the sample. This test ran sucessfully for about 2 weeks until it was dismantled. Since then, one full permeability test with heptane has been completed successfully, and another one is presently running with no trouble.

A second problem encountered is long testing times. Permeability tests with Lufkin clay and Hoytville clay are taking longer to complete than originally thought. It was stated earlier that tests are continued until at least 2 pore volumes of permeant liquid are passed through a sample so that a representative hydraulic conductivity can be determined. Based on tests in progress, it is estimated that at least 8 months are required to pass 2 or more pore volumes of permeant liquid through Lufkin clay samples under gradients less than 300. Hoytville clay samples under a gradient of 10 require about the same testing time.

RESULTS

Fewer than one-third of the planned tests have been completed. Preliminary data are presented for kaolinite, which is the soil for which the testing program is most nearly complete, and the permeant liquids water and methanol. Completion of the complete testing program will provide data for other soils, heptane as a permeant liquid, and sufficient replication data to allow measures of testing precision to be estimated.

Typical plots of hydraulic conductivity (k) versus number of pore volumes of flow are shown in Fig. 4 for the three types of permeameters and the permeant liquid methanol. The curves have similar shapes, but the compaction mold permeameter yields a somewhat higher hydraulic conductivity than the other two devices. The hydrualic gradient for these tests was 250 or 300.

Plots of k versus hydraulic gradient are presented in Figs. 5, 6, and 7 for the three types of permeameters, the soil type kaolinite, and the permeant liquids water and methanol. Each data point included within the figures represents a calculated value, obtained from a flow volume measure-

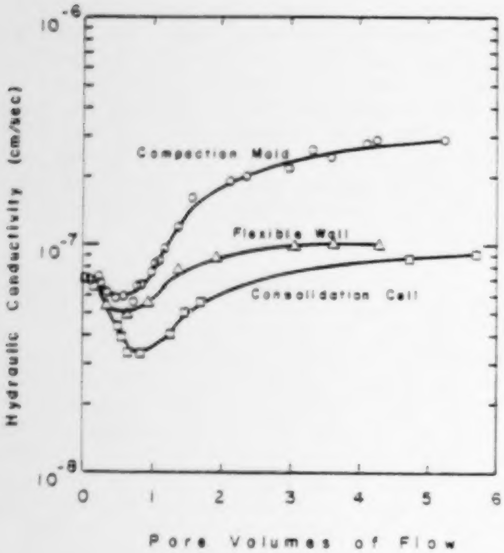

Figure 4. Hydraulic Conductivity Versus Number of Pore Volumes of Flow for Kaolinite permeated with Methanol at a Hydraulic Gradient of 250 or 300.

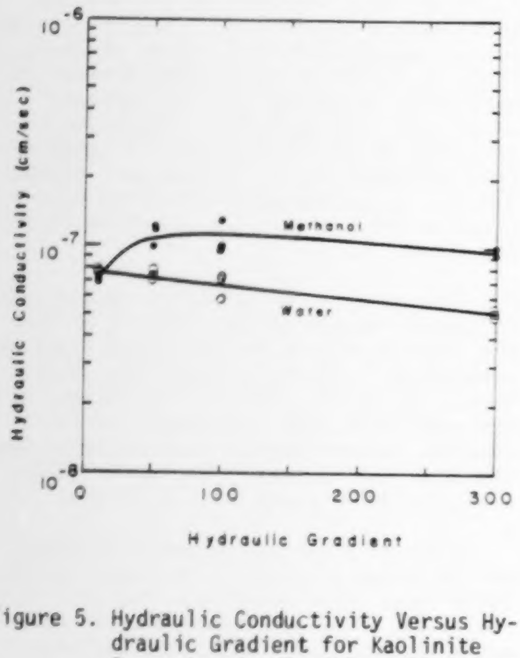

Figure 5. Hydraulic Conductivity Versus Hydraulic Gradient for Kaolinite Permeated in Flexible-Wall Permeameters.

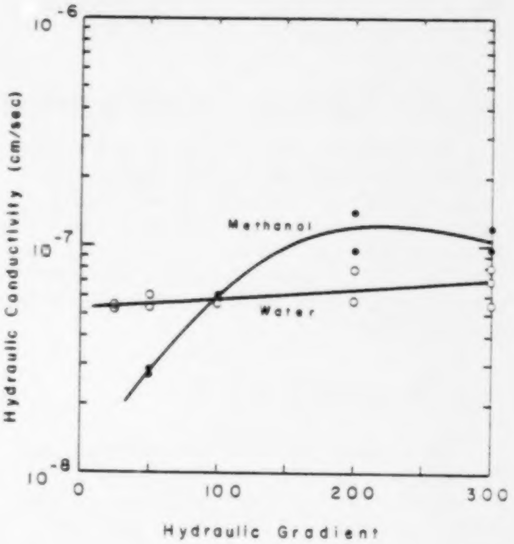

Figure 6. Hydraulic Conductivity Versus Hydraulic Gradient for Kaolinite Permeated in Consolidation Cell Permeameters.

ment taken at a point in time for one soil within one permeability test cell and inserted into the Darcy equation for flow through a porous medium. The trend of each curve was drawn after inspection of the data points. The conclusions drawn from these data are as follows:

1. At high hydraulic gradients (values of 150 or larger), kaolinite has a higher hydraulic conductivity to methanol than to water regardless of permeameter type.

2. At high hydraulic gradients, the flexible-wall and consolidation-cell permeameters yield similar hydraulic conductivities for both methanol and water; kaolinite is roughly twice as permeable to methanol as to water for these two types of permeameters.

3. At high gradients, use of compaction-mold permeameters leads to large scatter in measured hydraulic conductivity. On the average, compaction-mold devices showed kaolinite to be approximately 10 times more permeable to methanol than to water. The lowest values of k measured with the compaction-mold devices

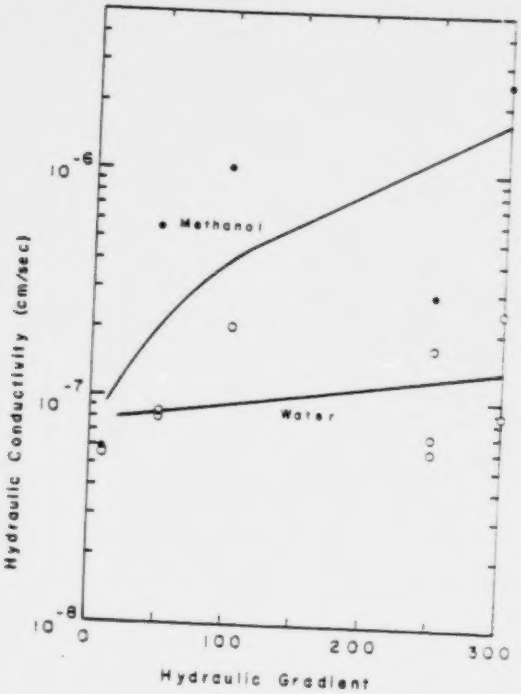

Figure 7. Hydraulic Conductivity Versus Hydraulic Gradient for Kaolinite Permeated in Compaction Mold Cell.

are nearly identical to values measured with the other two devices. It is possible that side-wall leakage contributed to the causes of large hydraulic conductivity in some of the tests.

4. With flexible-wall permeameters and two liquids and one soil, hydraulic gradient appears to have little effect on hydraulic conductivity (Fig. 5) for gradients between 50 and 300. At a hydraulic gradient of 10, the hydraulic conductivity of kaolinite to methanol is about half the value at higher gradients and is about the same as the value to water. As studies progress, data will show whether this trend is stable.

5. With consolidation-cell permeameters, hydraulic gradient has a very substantial effect on hydraulic conductivity (Fig. 6). At a hydraulic gradient of 50, k to methanol is only half of k to water, but at gradients of 200 to 300, k to methanol is twice as large as k to water. One possible explanation for the low k to methanol at low gradients is that the pressure head at low gradients is not large enough to cause full saturation of the soil. As methanol flows through soil, the pressure drops and any gas dissolved in methanol beyond the solubility limit at the reduced pressure would be released. Because the solubility of air in methanol is approximately 10 times the solubility of air in water, the opportunity for release of gas from solution is much greater with methanol than with water. The high backpressure used with flexible-wall permeameters probably prevented formation of any significant volume of gas with flexible-wall tests.

6. There is too much scatter in the plots of k versus hydraulic gradient for compaction-mold permeameters (Fig. 7.) to draw any definite conclusions. However, data collected so far appear to indicate a trend of increasing hydraulic gradient causing an increase in hydraulic conductivity of kaolinite to both water and methanol. Completion of the testing program in August, 1984 is expected to result in data which confirm the actual trends.

ACKNOWLEDGMENTS

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COMPARISON OF COLUMN AND BATCH METHODS FOR PREDICTING COMPOSITION OF HAZARDOUS WASTE LEACHATE

Danny R. Jackson, Benjamin C. Garrett, and Thomas A. Bishop
Analytical Chemistry and Applied Statistics Sections
Battelle-Columbus Laboratories,
Columbus, Ohio 43201

ABSTRACT

Inorganic and organic analytes were leached from four waste samples using batch and column leaching methods. Leachate concentration profiles were constructed from sequential leaching of waste with distilled-deionized water using a combined solution to waste ratio of 40:1. Leachate profiles produced by the batch and column methods were compared in terms of a fitted leaching profile function and variation of the experimental data. Leachate profiles produced by the two methods were significantly different for 12 of the 16 reported analytes. Variation of experimental data, as represented by relative standard deviation, was over twice as great for the column method than for the batch method. This result was attributed to varying degrees of channeling that may have occurred during leaching of waste constituents using the column method. The batch extraction method offers advantages through its greater reproducibility and simplistic design, while the column method is more realistic in simulating leaching processes which occur under field conditions.

INTRODUCTION

Various laboratory techniques have been reported for generating and characterizing leachate from solid hazardous waste and are generally grouped into batch and column extraction methods (1). A batch extraction method involves the mechanical mixing of a unit volume of water, or an alternative solution, with a unit mass of hazardous waste. This method has been noted for its ease of operation and low experimental variation (2). A column extraction method involves the continuous flow of liquid through a fixed bed of solid waste. Leachate generated by the column method is reportedly more representative of leachate derived from a disposal site than is the leachate from the batch method (3). Column procedures generally include a liquid to solid ratio which more closely represents a field situation. The mechanism of contacting a fixed body of waste with a transient liquid resembles the leaching mechanism imparted by gravity flow of liquid through a waste disposal site.

The objective of this study was to compare differences in concentration of leachate constituents and experimental variation derived from batch and column extraction methods using samples of four representative wastes. The column leaching method was designed to be comparable to the batch method in terms of operational parameters such as liquid to waste ratio and leaching time. This standardization allowed comparisons to be based primarily on differences in waste constituents dissolved by (1) flowing water through a static bed of waste (column method) and (2) constantly agitating a waste-water suspension (batch method). Leachate profiles were generated based on multiple sequential extractions of waste samples and results were compared using a statistical model.

APPROACH

Four waste samples having diverse physicochemical characteristics were selected for the leaching experiments (4). Electroplating sludge and fly ash were selected as representatives of inorganic solid wastes. A filter cake sludge and a liquid (polystill bottoms) were selected as representatives of organic wastes. Several analytes were analyzed for each waste. Metals were determined by Inductively Coupled Argon Plasma (ICAP), while volatile organic compounds were determined by gas chromatography (4). Three replications were used for each waste and extraction procedure.

Extraction Procedures. The Solid Waste Leaching Procedure (SWLP), described by Garrett et al. (5), was used as the batch method for extracting waste samples in a sequential manner. This procedure specifies sequentially mixing 100 µg of waste with four 1-L aliquots of distilled water. Thus, each leaching sequence constitutes a liquid to waste ratio of 10:1, with a combined waste to liquid ratio of 40:1. This sequential mode of waste extraction facilitates the construction of leachate profiles from which intensity (concentration) and capacity (buffering) factors can be evaluated.

A column extraction procedure was designed to provide leaching profiles of waste samples comparable to those generated by the batch procedure. Details of the column method are described by Jackson et al. (4). A waste sample is mixed with sand prior to placement in a column to increase permeability and reduce channeling and particle migration. The packed column was leached with distilled-deionized water at a rate of 0.93 mL/minute. This leaching rate was prescribed to leach each 100-g sample of waste with four 1-L fractions of water over four 18-hour time periods. Thus, the total volume of water contacting each 100-g sample of waste per 18-hour time interval was equivalent to that of the batch method.

Timer-regulated rotary valves apportioned the various leachate fractions into Tedlar® collection bags. The rotary valve timers were set to divide the first 1-L leaching fraction into three equal subfractions, and the second 1-L fraction into two equal subfractions. The third and fourth leaching fractions were not subdivided. This leaching sequence was performed to provide greater resolution of the leaching profile in the liquid to waste ratio portion of the profile where greater changes in analyte concentrations were expected.

Statistical Model. Comparison of the batch and column extraction methods is based on a statistical model that describes the deterministic and random experimental factors influencing the leachate data (4). Because the data ranged over several orders of magnitude, the model describes the natural logarithms of the basic concentration data. The deterministic factors control the average concentration levels of the analytes in the leachate. This average concentration is a function of the volume of liquid contacting the waste, denoted by f(V), where V represents the volume.

In addition to deterministic factors, several sources of random variation affect the data. Potentially significant sources of variation are: (1) replication, (2) leaching processes within a given 100-g sample, and (3) the analytical determination.

The basic form for the statistical model for method k (k=1 for batch, k=2 for column) is given by:

$$\ell n\ Y_{kij} = f_k(V_j)+R_{ki}+\gamma_{kij} \quad \text{eq.1}$$

where Y_{kij} is the observed concentration measurement after V_j liters of water have contacted the ith 100-g sample. The function $f_k(V_j)$ describes the average concentration level as a function of volume V_j. The random component R_{ki} represents the random effect associated with replication i (i = 1,2,3) and γ_{kij} is the random component representing the combined leaching and analytical measurement effects. These two sources of variability cannot be separated since single analytical measurements were made on the leachate samples. The $\{R_{ki}\}$ are assumed to be independent and normally distributed with expected value zero and variance $\sigma^2_{R_k}$. The components $\{\gamma_{kij}\}$ are assumed to be independent and normally distributed with expected value zero and variance $\sigma^2_{L_k}$.

The actual form of the deterministic profile function $f_k(v)$ is unknown, but it can be approximated by a third-order polynomial equation. Therefore, the statistical model used to analyze the laboratory data is given by:

$$\ell n\, Y_{kij} = \beta_{0k} + \beta_{1k} \cdot V_j +$$

$$\beta_{2K} \cdot V^2_j + \beta_{3k} \cdot V^3_j + R_{ki} + \gamma_{kij} \quad \text{eq. 2}$$

The last two terms of equation 2 also contain the variation between the polynomial equation and the unknown function $f_k(V)$.

The statistical software package BMDP3V (5) was used to estimate the model parameters via a maximum likelihood estimation procedure. The polynomial coefficients β_{0k}, β_{1k}^{k} β_{2k}, and β_{3k} and the variance components $\sigma^2_{R_k}$ and $\sigma^2_{L_k}$ were estimated by this technique for both the batch and column procedures using the laboratory leachate data. The fitted profile functions based on these estimated coefficients are presented as the curved lines in Figures 1-4. Formal hypotheses were constructed and statistical tests performed to compare these parameters across methods to determine if significant differences existed in either the leachate profiles or the level of experimental variation associated with each method. The results of these analyses are summarized in Table 1.

PROBLEMS ENCOUNTERED

A multichannel peristaltic pump was initially employed in the column extraction procedure in order to lower costs associated with the procedure. However, liquid flow through the columns was diminished over the 72 hour leaching sequence. This diminished flow was attributed to slight increases in back pressure created by particle migration in the waste columns and a decrease in the elasticity of the tubing in contact with the pump rollers. This problem was solved by replacing the peristaltic pump with three positive displacement pumps.

A second problem encountered involved the apparent inadequacy of the statistical model to fit closely the highly variable experimental data of certain leachate profiles. In some cases, abrupt changes in the leachate profiles from the column method required more flexibility than the third order polynomial function could provide. This problem was most notable in leachate profiles of the polystill bottoms waste (Figure 4). New statistical models are being considered for fitting experimental data of a highly variable nature (4).

RESULTS

Leachate Profiles. Evaluation of intensity and capacity factors can be made using information from the leachate profiles (Figures 1-4). For example, not only is the pH of electroplating sludge relatively high (pH 7-8), but this waste is also highly buffered against the neutralizing effect of sequential leaching with water in excess of a 40:1 liquid to waste ratio. In contrast, pH of fly ash leachate was initially at 3.5 and increased to approximately 6.5 over the course of sequential leaching. A single extraction of waste would not provide insight into the capacity of the waste to sustain a given concentration of analyte in leachate.

Waste leachate profiles were constructed from batch and column extractions using 4 and 7 successive leaching fractions, respectively. Fewer leachate fractions were collected using the batch procedure because of the added time expenditure required for filtering leachates each time an additional leachate fraction was initiated. Alternatively, fractionation of leachate samples from the column procedure can be accomplished readily with little additional time required, due to the timer-sequenced rotary valves regulating leachate collection. Reduction of the liquid to waste ratio used for the intial leachate fractions from the column procedure can provide greater resolution of the overall leachate profile. This greater resolution is especially desirable in cases where initial analyte concentrations in leachate are high and the capacity for leaching is relatively low (Figure 4). Additional leachate fractions are not as important to resolving a leaching profile for wastes which are buffered to a great extent such as the pH of electroplating waste (Figure 1).

Experimental Variation. Components of variation associated with the leaching methods were estimated and compared. The random variation was classified into two distinct categories: (1) differences among the three replicate waste samples used to generate each leachate profile and (2) combined differences attributable to the sequential leaching and analytical measurement processes. Previous investigations have indicated that experimental variation due to the analytical measurement process is negligible compared to that due to sequential leaching (7).

In almost all cases, the replicate variance component (σ_R^2) associated with both methods was less than the variance associated with sequential leaching (σ_l^2) (Table 1). This trend was notably significant for the batch method. Replicate variation for the batch method was approximately three-fold lower than that for the column method (Table 1). This finding can be attributed to the more thorough agitation of samples analyzed by the batch method. The mean overall experimental variability for the column method, as represented by replicate and leaching profile components of variation, was over twice as great as the variability for the batch method.

Variance attributed to sequential leaching (σ_L^2) was greater for the column method than for the batch method in all but two cases (Table 1). This difference is attributable in part to the lack of fit of the model to the experimental data from the column extractions. While a few cases of high σ_L^2 values are attributable to model deficiencies, the order of magnitude difference between overall mean values of σ_L^2 for the batch and column methods (Table 1) represents greater experimental variation on the part of the column method. This variation may result from non-uniform water flow through the waste column during the leaching process. Sand was added to the waste samples in order to reduce this variance by increasing porosity and decreasing channelization.

CONCLUSIONS

Column methods used previously for extracting hazardous waste have focused primarily on an attempt to simulate field leaching processes closely. These methods have generally employed gravity-fed leaching medium and, consequently, low flow rates. Leaching relatively impermeable wastes have been problematic using these methods, and results have been highly variable (8). The column method presented in this study was developed to reduce experimentation time greatly through an accelerated flow rate. This greater flow rate was facilitated through the use of sand incorporation with the waste prior to leaching. While this operation may compromise the simulation of natural leaching processes, it greatly increases the utility of a method which is less aggressive and conceptually more realistic than the batch method.

The batch extraction method offers an advantageous approach to extraction of waste constituents through its greater reproducibility and simplistic design. The batch method can be set up and used routinely by laboratory personnel more easily than the column method. The lower inherent experimental variation associated with the batch method should facilitate more satisfactory interlaboratory comparisons which are a necessary part of standardizing an extraction procedure for regulatory functions.

In summary, both batch and column extraction methods were effective in generating useful leachate profiles for evaluating potentially hazardous wastes. Although useful data can be produced by these methods, the relative accuracy of predicting levels of analytes leached from landfilled wastes remains uncertain.

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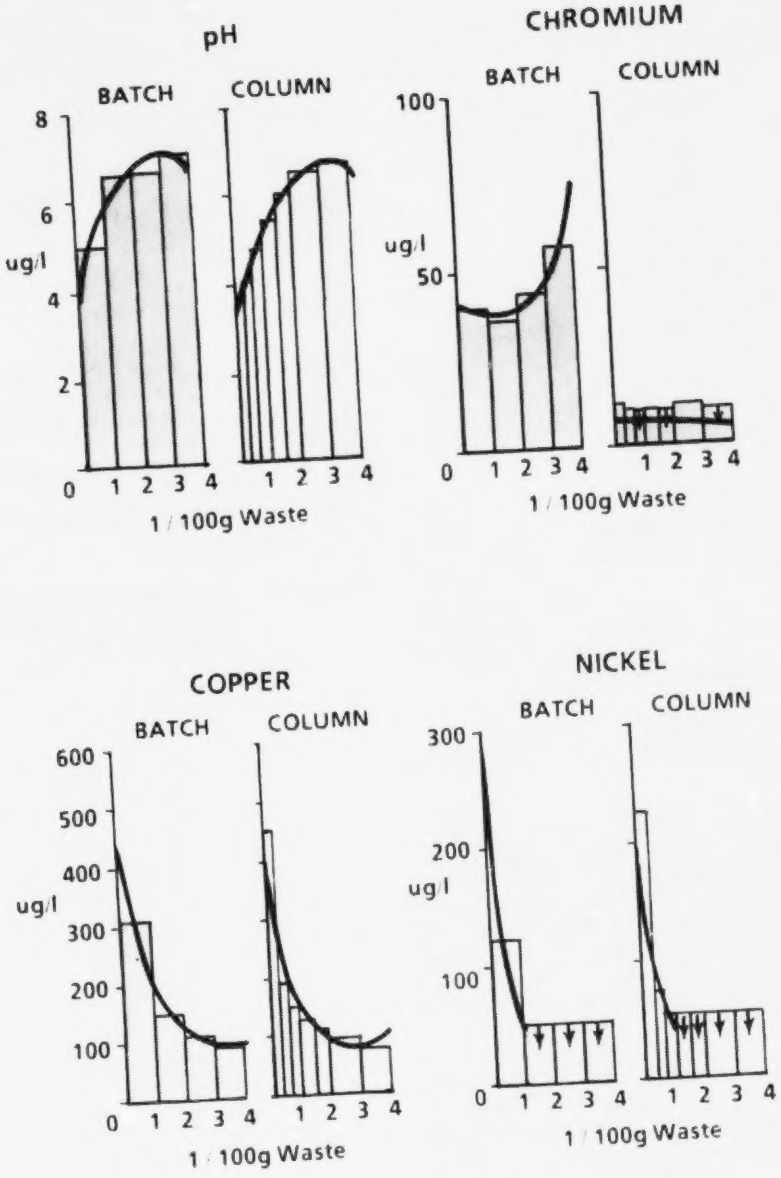
Figure 1. Leachate profiles for Electroplating Sludge. (↓ denotes less than detection limit)

Figure 2. Leachate Profiles for Fly Ash.

Figure 3. Leachate Profiles for Filter Cake.

Figure 4. Leachate Profiles for Polystill Bottoms. (↓ denotes less than detection limit)



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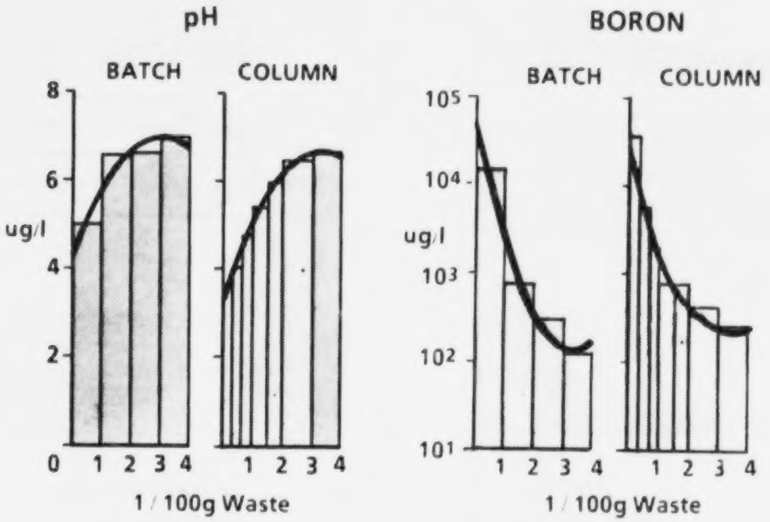

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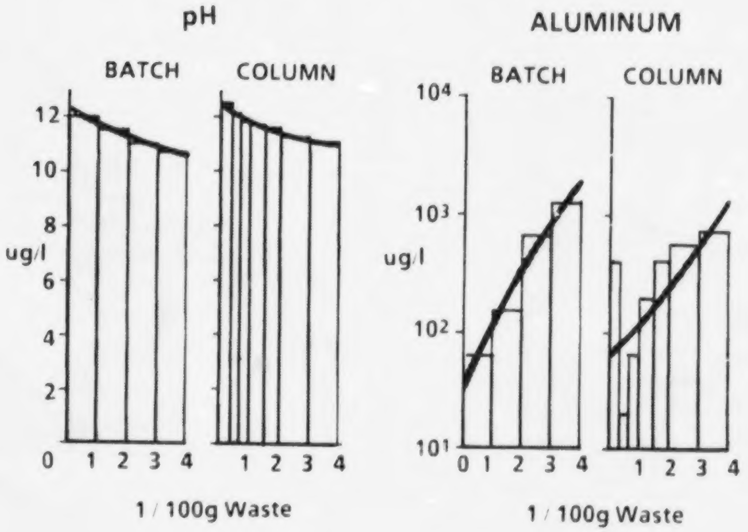

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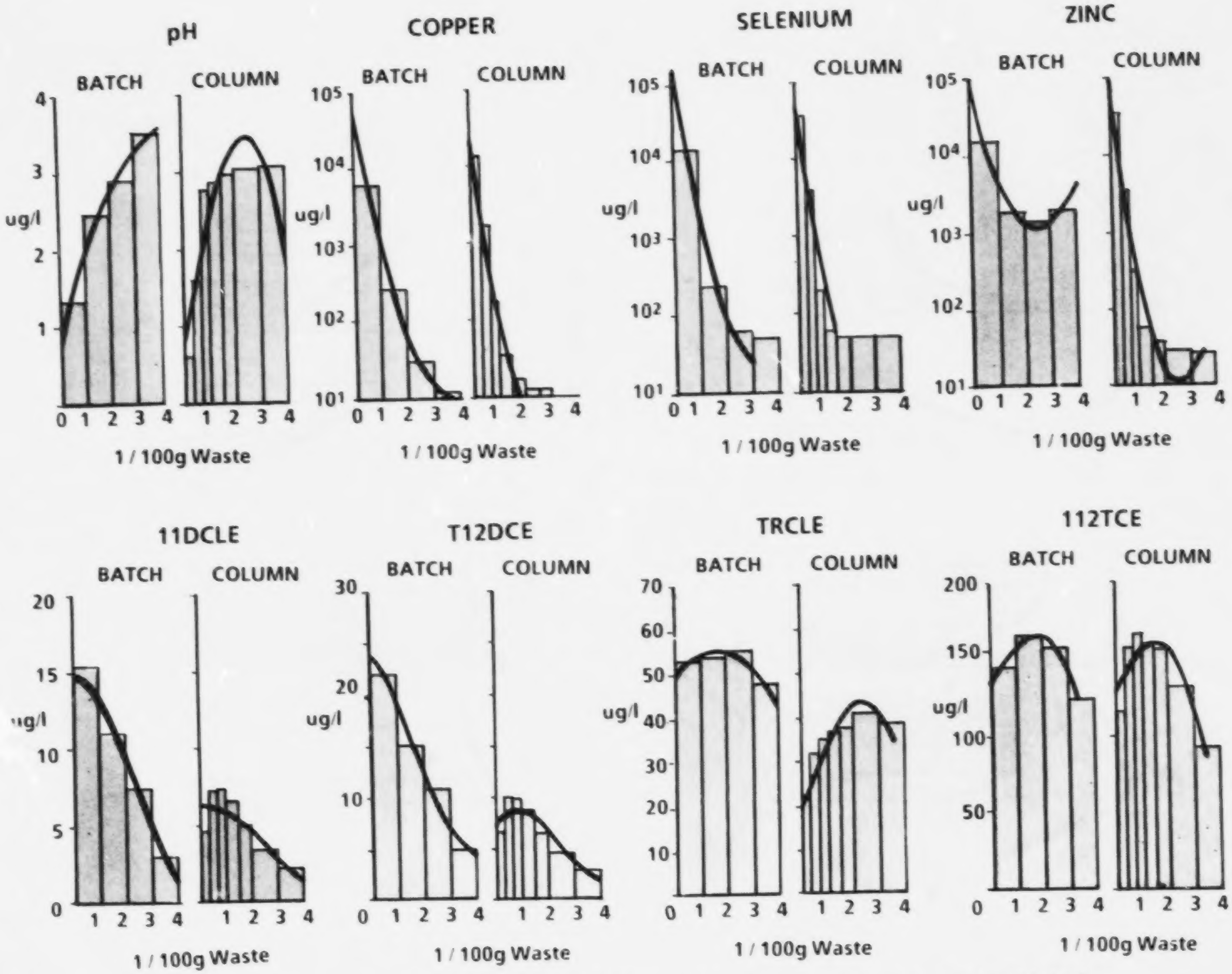

Figure 4. Leachate Profiles for Polystill Bottoms. (↓ denotes less than detection limits)

TABLE 1. SUMMARY OF THE VARIANCE COMPONENTS AND LEACHATE PROFILE ANALYSES

		Sources of Method Variation						Leachate Profile Comparison		
		Replication Variance			Combined Leaching & Analytical Variance			Order of Polynomial Fit to Leaching Data		
Waste Type	Analyte	Batch (σ^2_R)	Col (σ^2_R)	D?	Batch (σ^2_L)	Col (σ^2_L)	D?	Batch	Col	D?
Electroplate Sludge	Ca	0.0002	0.0568	Yes	0.0001	0.1256	Yes	Quadratic	Quadratic	No
	Cr	0.0047	0.0415	No	0.0009	0.1196	Yes	Cubic	Constant	Yes
	Cu	0.0000	0.0060	Yes	0.0009	0.0214	Yes	Quadratic	Quadratic	No
	Ni	0.0000	0.0018	Yes	0.0005	0.0255	Yes	Quadratic	Quadratic	No
	pH	0.0003	0.0811	No	0.0022	0.0673	Yes	Constant	Constant	Yes
Fly Ash	B	0.0024	0.2314	Yes	0.0059	0.1782	Yes	Quadratic	Quadratic	Yes
	Ca	0.0015	0.2228	Yes	0.0012	1.4459	Yes	Quadratic	Quadratic	No
	pH	0.0553	0.0000	Yes	0.0822	0.1363	No	Quadratic	Quadratic	Yes
Filter Cake	Al	0.0000	0.0633	Yes	0.0190	1.0050	Yes	Linear	Linear	No
	Ba	0.0020	0.0000	Yes	0.0017	0.0465	Yes	Cubic	Linear	Yes
	pH	0.0000	0.0011	Yes	0.0007	0.0096	Yes	Cubic	Cubic	Yes
Polystill Bottoms	Cu	0.0059	0.0518	No	0.1413	0.1217	No	Quadratic	Quadratic	Yes
	Fe	0.0110	0.0812	No	0.1172	0.0652	No	Quadratic	Cubic	Yes
	Se	0.0000	0.0090	Yes	0.0101	0.1820	Yes	Quadratic	Quadratic	Yes
	Mo	0.0000	0.0000	No	0.0405	0.3724	Yes	Quadratic	Cubic	Yes
	Zn	0.0000	0.0346	Yes	0.0018	0.1018	Yes	Quadratic	Quadratic	Yes
	pH	0.0003	0.0028	No	0.0014	0.0418	Yes	Quadratic	Cubic	Yes
	11DCLE*	0.0026	0.0328	No	0.0175	0.0355	No	Constant	Constant	Yes
	T12DCE#	0.0045	0.0249	No	0.0303	0.0388	No	Quadratic	Quadratic	Yes
	12DCLE	0.0000	0.0000	No	0.0129	0.0683	Yes	Quadratic	Quadratic	Yes
	CCL4	0.0012	0.0000	Yes	0.0097	0.0861	Yes	Constant	Linear	Yes
	TRCLE**	0.0000	0.0038	Yes	0.0089	0.0406	Yes	Constant	Linear	Yes
	112TCE##	0.0000	0.0000	No	0.0043	0.0173	Yes	Cubic	Cubic	No
	Unknown	0.0000	0.0000	No	0.0023	0.0204	Yes	Linear	Linear	No
	TCLEE	0.0006	0.0000	Yes	0.0067	0.0551	Yes	Constant	Constant	No

D? Is there a statistically significant difference (5% level)
* 1,1-Dichloroethane
# Trans-1,2-dichloroethene
** Trichloroethene
## 1,1,2-Trichloroethane

USE OF BATCH ADSORPTION PROCEDURES FOR DESIGNING EARTHEN LINERS FOR LANDFILLS

C. C. Ainsworth, R. A. Griffin, I. G. Krapac and W. R. Roy

Illinois State Geological Survey
615 East Peabody Drive
Champaign, Illinois 61820

ABSTRACT

An investigation is being undertaken to develop a "Batch Sorption" procedure and scientific documentation for hazardous wastes on soils and soil constituents. The procedure will help in evaluating various earthen materials with respect to their ability to attenuate hazardous waste. A very simple procedure has been adopted and is now being tested as to its flexibility, reproducibility, and usefulness. The procedure will be revised and tested using various soils from different parts of the country. Soil to solution ratio, most effective mixing method, separation techniques, and sample size are just some of the variables that are being addressed in this investigation. As each question is studied the procedure is revised and upgraded to reflect the data obtained. In using this systematic approach, the procedure will be well documented by laboratory experimentation and data and will hopefully be of use in critical evaluations of an earthen material's ability to attenuate pollutants.

INTRODUCTION

The retention of chemical species in various soils and soil constituents have been studied for many years. The adsorption of inorganic cations and anions by clays and soils (Bingham et al., 1964; Griffin and Shimp, 1976; Frost and Griffin, 1977; Harter, 1979 and others) has been investigated; as has organic compounds (Griffin et al., 1978; Chou and Griffin, 1981; Hassett, Banwart, and Griffin, 1983). Although there are many variations, the "batch" adsorption technique has been widely used. This consists of mixing a solution of known composition and concentration with a mass of soil for a given period of time. The solution is then filtered and analyzed for concentration changes to determine adsorption by the soil. This has been called the standard or traditional "batch" technique. In point of fact there is nothing truely standard about the procedure. In reviewing just a portion of the literature, 80 batch adsorption studies were found using various adsorbates and adsorbents. Of these, few were procedurally comparable.

Apart from the inherent variability of different soils there are a considerable number of factors that affect the sorption of a given constituent. For inorganic species some of these are temperature, method of mixing, composition and concentration of the solution, and moisture content (Barrow, 1978). Organic species are much more complicated; this is due to the need to identify and control various reactions that would reduce or in some way affect the precision and accuracy of the results. Photodegradation, polymerization, microbial degradation, hydrolysis, and volatilization are reactions that could effect the outcome of an organic sorption study.

The development of uniform batch-test sorption procedures would enable investigators to obtain sorption-retention data of known reproducibility under standard conditions. This would help in comparing and evaluating various materials for their suitability as landfill liners. It would also allow calculation of minimum thicknesses of clay liners to remove pollutants from landfill leachates (Griffin et al., 1976).

To facilitate the comparisons of various systems (adsorbent/adsorbate) sorption data has been fitted to adsorption curves (Sibbesen, 1981; Barrow, 1978). However, if the techniques used to obtain the data are not comparable then the comparisons that are made may be erroneous. It is the hope of this investigation that a procedure and guidelines can be developed to allow for useful and reproducible collection of adsorption data for evaluation of landfill liner materials.

PURPOSE

The purpose of this research project is to develop a Technical Resource Document and a Background Document to be used for performing batch type sorption studies and for using this data to estimate pollutant retention by earth material liners at hazardous waste disposal facilities. The specific objectives are:

1. To develop standardized procedures for collection of sorption data.

2. To prepare a document detailing the routine use of the procedures.

3. To prepare a background document describing the scientific basis and rationale behind the procedures developed and recommended for use.

In using a batch sorption procedure to develop a sorption curve for a given system, the soil to solution ratio used for an investigation may be predicted upon the ability to detect the steady-state concentration of the specie of interest. Hassett et al. (1980), using a radioisotope labelling as a means of detection, needed three different soil to solution ratios to determine sorption properties of 14 organic compounds onto 14 soils and sediments. Without the use of isotopic labelling the soil to solution ratios would probably have been much wider and more varied. In this respect a single predetermined soil to solution ratio is not feasible.

A single sorption curve (equilibrium concentration versus amount of sorption), should, in theory, describe a given system at equilibrium no matter what the soil to solution ratio. Whether one holds the concentration (initial) constant and varies the soil to solution ratio or vice versa, the same adsorption curve should describe both techniques. This of course is true provided all other parameters are equal or accounted for in the adsorption curve. Griffin and Au (1977) found Pb sorption on Ca-montmorillonite to be apparently dependent upon the soil to solution ratio. However, once the Ca ion activity in solution was accounted for, a single adsorption curve described the system regardless of the soil to solution ratio.

In more complex systems, such as soils which contain many materials in addition to clay minerals, results of soil to solution ratio studies have been less straightforward. Using Atrazine (2-chloro-4-(ethylamino)-6-isopropylamino-5-triazine) as the adsorbate, Dao and Lavy (1978) and Anderson et al. (1980) found that soil to solution ratio had no effect on the amount sorbed by soil. Nearpass (1967), and Green and Obien (1969) found a 1.4 fold decrease and 1.6 fold increase, respectively, in Atrazine sorption with an increase in soil to solution ratios. However, both felt these were statistically insignificant. Grover and Hance (1970) saw a decrease in the Freundlich constant (K_f), by a factor of 2.6 when the soil:solution ratio was changed from 1:10 to 1:0.25. Koskinen and Cheng (1983) also found differences in the K_f for 2,4,5-T sorption on soils which were ascribed to soil:solution ratio. Their results indicated the variation was only present at higher soil to solution ratios.

While a great number of systems reach steady-state conditions rapidly others require days and weeks. Bar-Yosef (1979) studied Zn sorption on soils and determined the steady-state conditions to be reached only after 16 to 168 hours. Hope and Syers (1976) found that phosphate sorption in soils had not reached equilibrium after 146 hours. R. E. White (1966) found equilibrium between phosphate and certain soils to be attained only after 120 days. W. R. Roy (unpublished data) found Mo, As, and P to take up to 5 days to reach steady-state conditions. Besides the dependence on the soil used or constituent of interest the rate at which sorption occurs (and hence attainment of steady-state) also has been shown to be dependent upon soil:solution ratio, vigor of shaking, and method of shaking (Barrow and Shaw, 1979). Unfortunately, the dependent variables mentioned above are not predictable. Therefore, it would be presumptuous to arbitrarily set a time interval to carry out the procedure.

However, beyond about a 24 hour period the investigator must be conscious of concomitant reactions that may affect the adsorption study. Of primary importance is microbial assimilation or degradation. This is particularly true of organics.

Although the literature does suggest that low soil to solution ratios are less likely to cause problems, it can be seen from the previous discussion that work remains to be done on this topic. Even if the rationale has not been worked out for a procedure which accounts for this phenomenon, it does not preclude the practical application of an empirical soil to solution ratio given certain constraints. This is one of the areas that is actively being pursued via laboratory investigations in this project.

While the procedure for organics may be similar to inorganics, the work to develop the laboratory basis for such a procedure is much slower. This is primarily due to analytical considerations. However, tests must be designed to allow for the determination of various side reactions that may bias the batch sorption study results (i.e.: photodegradation, volatilization, etc.). Therefore, organics are not as easily characterized as inorganic pollutants with respect to developing documentation of a sorption procedure.

APPROACH

The approach to developing a useful batch adsorption procedure is based on the premise that to be useful it must be flexible enough to accomodate those that would use it and have a well founded scientific rationale. The flexibility of a procedure is seen by the investigator's ability to use various techniques and equipment without altering the results of a given study. Each step and option (point of flexibility) within the procedure must be shown to have a rational and scientific basis. The latter is to be determined through the use of the published literature and laboratory studies.

Figure 1 is a flow chart of the initial proposed procedure that was based on a draft procedure developed by ASTM Committee D34.02.03. From this, one may identify the points at which the procedure may be unnecessarily confining. These are: 1) mass of soil needed, 2) soil:solution ratio, 3) the type of container, 4) type of mixing apparatus, 5) time of shaking and, 6) mode of separation. Other points that may need to be studied are temperature and ionic strength at which the investigations are to be carried out.

As the procedure is run and points investigated, a new generation of the procedure is developed. This is then tested for reproducibility through an ASTM sensitivity analysis using several volunteer laboratories. The cooperating laboratories run the procedure on a given soil using prescribed solutions. Results and comments on the procedure are then correlated. This is very useful in identifying problems and appropriate changes. From the first test the major problem identified was that of shaking vigor.

Concomitant to the actual testing of the procedure itself, laboratory studies are being carried out to investigate various improvements in the procedures such as methods of separations, variations in sample size, etc. Also, attempts are being made to determime how to best delineate the range of solutions used, soil to solution ratio, and time of mixing. At the present time only one soil (Catlin silt loam) and two adsorbates (arsenate and cadmium) are being used for inorganic adsorption tests. Once a procedure is completely worked out, it will be verified on five additional soils from various parts of the United States.

RESULTS

Most of the laboratory work to date has been the collection and characterization of the seven soils to be used in the investigation. This includes, mineralogy, surface area (N_2 B.E.T.), particle size distribution, cation exchange, native cation and anion determinations (both H_2O, KCl, and NH_4Cl extracts) and various other tests. Some work has been done on the points of interest in the procedure. A

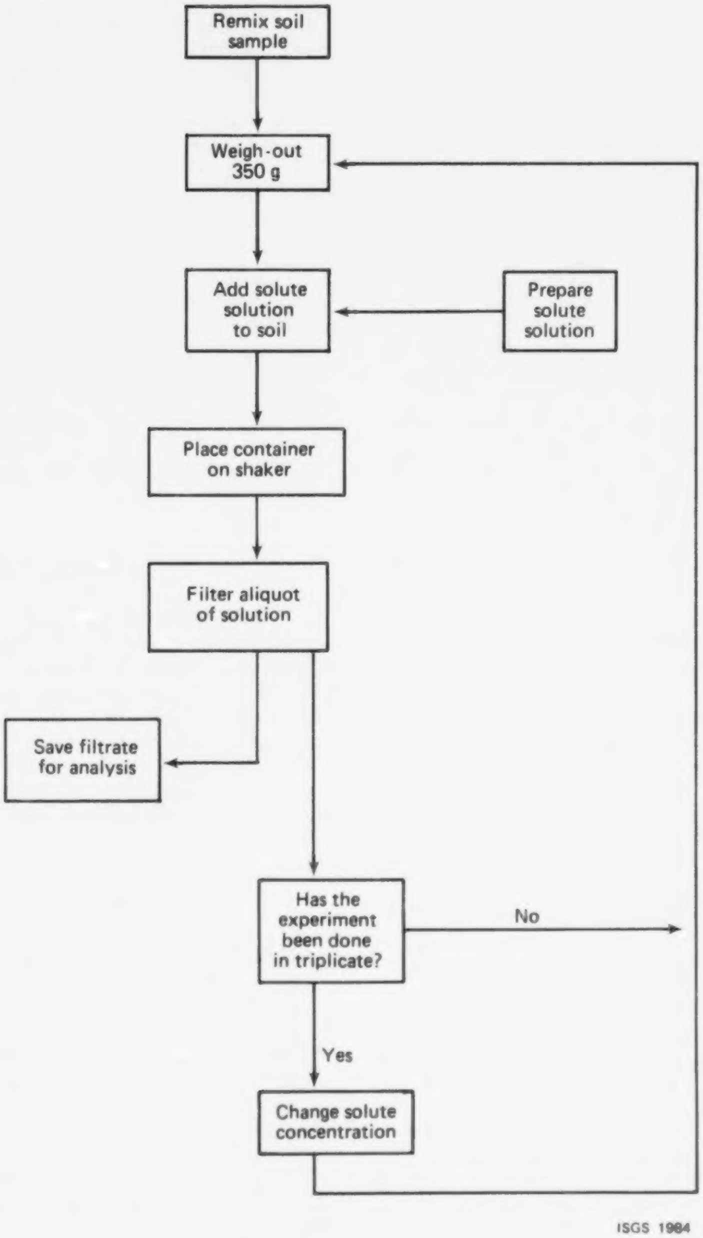
Remix soil sample
Weigh-out 350 g
Add solute solution to soil
Prepare solute solution
Place container on shaker
Filter aliquot of solution
Save filtrate for analysis
Has the experiment been done in triplicate?
No
Yes
Change solute concentration

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Figure 1. Flow chart for sensitivity test.

Catlin A_1 horizon (fine silty, mixed mesio, Typic Argiudoll) has been used as the sorbent in these initial studies. This soil has 2-3% organic carbon, 24% clay, 65% silt, 11% sand and has a pH of 7.1 (1:1; H_2O).

Using 200 ppm of Cd (as $CdCl_2$) dissolved in deionized H_2O as the sorbate, a kinetics study was carried out using 350 g soil in a 1:4 soil:solution ratio. Samples were allowed to shake on a reciprocating shaker (100 strokes/min; 1.25 inch throw) for periods of 1 to 32 hours. Samples were filtered and then analyzed using an inductively coupled argon plasma (ICAP). In conjunction with this study, triplicate samples of the above prescription were allowed to shake or stir (paddle stirrer) at various speeds and displacements. Also, using a 200 ppm arsenate solution (as Na_2HAsO_4), a sample size-separation study was conducted. This consisted of triplicate samples of Catlin soil at a 1:4 ratio of the As solution using either 350 g or 50 g of soil. The samples and 2 separation techniques (12 runs total) were shaken at 100 strokes/min and 1.25 inch displacement for 24 hours on a reciprocating shaker. Samples were then separated using either filtration or centrifugation. Filtration was accomplished using four 25 mL aliquots passed through a 0.45 μm pore size filter; the initial aliquot was discarded. The centrifugation used either 50 mL or 150 mL of the suspension in nalgene tubes at 1.6×10^4 or 5.0×10^3 rpm, respectively, for 30 minutes at constant temperature.

Figure 2 illustrates that the Catlin soil/Cd solution reached a steady-state Cd concentration in approximately 2 hours. However, after shaking similar samples for 24 hours at various speeds, none of the other suspensions had attained the final concentration that set C (Table 1) had after 2 hours. Barrow (1978) showed that various shaking vigors could affect the speed at which a steady-state condition was reached. But, he also demonstrated that either ped destruction or abrading of surfaces could also cause sorption to take place at an increased rate. This latter point does not happen to every soil. It may well be that the differences observed here are a function of one or both of the above phenomena. Since this experiment was run, an end-over-end tumbler has also been employed in the investigations, which promises to provide superior results.

The results of the sample size-separation study demonstrated that sample size need not be as voluminous as originally proposed (Table 2). Also, it would appear that the separation can be obtained through filtration or centrifugation without sacrificing reproducibility.

While these studies are preliminary and the breadth of samples narrow, the results do help in identifying problems. As a consequence of these studies the maximum mass of soil has been decreased from 350 g to 70 g, filtration or centrifugation has been adopted and, due to other work similar to the above, the soil/solution ratio for the Catlin soil has been revised to 1:20. Now that the seven soils to be used in the investigation have been collected and characterized, the breadth of experiments involving both adsorbent and adsorbate will be extended. Through this type of systematic investigation it is felt that a reliable, well documented procedure can be produced that will be useful in assisting in the selection of earthen materials for landfill liners.

ACKNOWLEDGEMNTS

Financial assistance from the U. S. Environmental Protection Agency, Solid and Hazardous Waste Research Division, Award No. R-810245-01 and the assistance of our project officer, Dr. Michael Roulier, are gratefully acknowledged. Also, we would like to thank ASTM and ASTM D34.02.03 participating laboratories for giving of their time and effort so freely.

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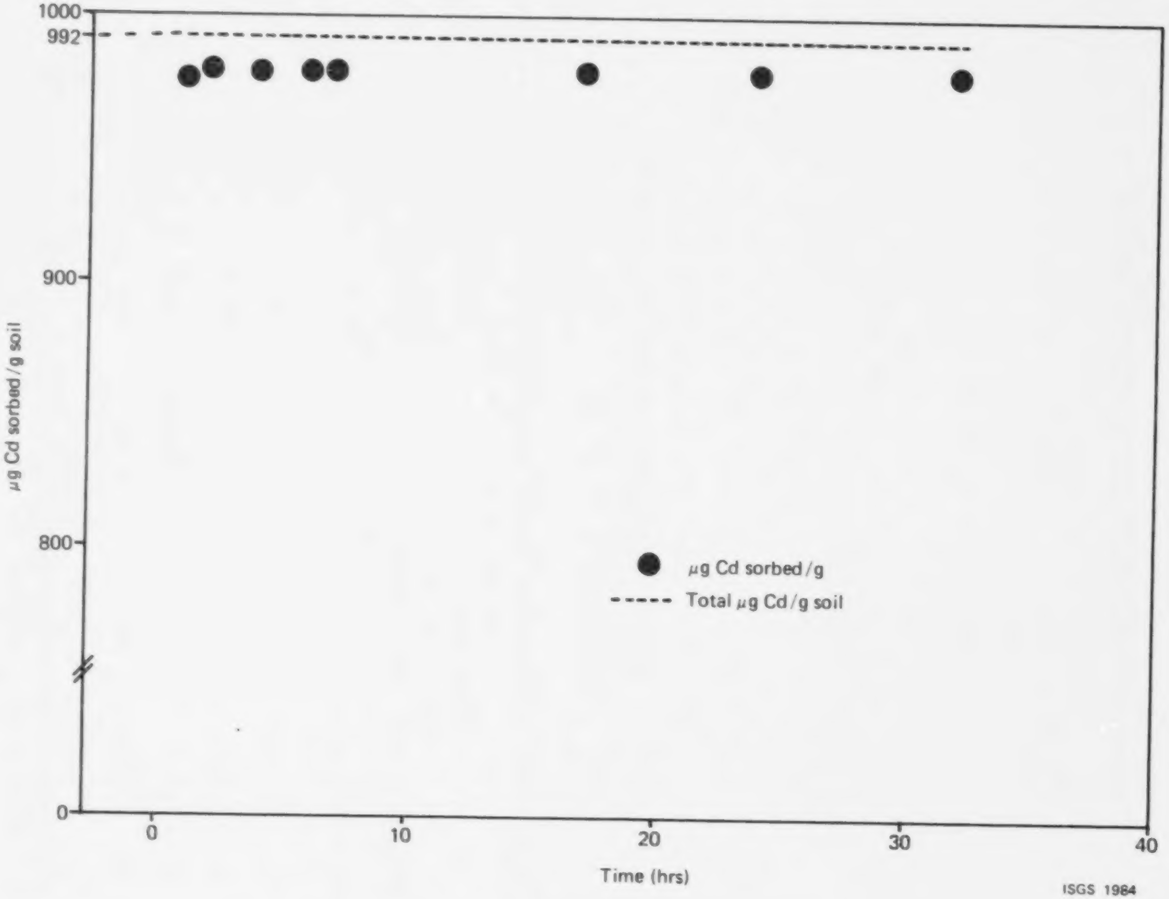

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Figure 2. Sorption of Cd on Catlin soil with time using the reciprocating shaker at 100 strokes/min and a displacement of 1.25 inches.

TABLE 1. RESULTS OF 24 HOUR SORPTION STUDY USING VARIOUS VIGOR OF SHAKING AND AN INITIAL Cd CONCENTRATION OF 200 ppm

Set	Cd in Solution ppm	Shaker Rate strokes/min	Shaker Rate throw (inch)
A	13.82*	59	3"
B	19.3*	70	1.25"
C	1.78*	100	1.25"
D	3.1*	paddle stirrer	

*Each concentration is the average of 3 separate runs.

TABLE 2. RESULTS OF THE SAMPLE SIZE-SEPARATION STUDY USING THE CATLIN SOIL AND AN INITIAL As CONCENTRATION OF 200 ppm

	200 ppm initial As solution				
	350 g soil		50 g soil		
	1400 mL solution		200 mL solution		
Sample	Filter	Centrifuge*	Filter	Centrifuge**	Centrifuge*
	As in solution (ppm)				
1	128.0	129.0	126.5	124.5	129.5
2	131.0	128.0	128.0	126.5	127.0
3	127.0	127.0	131.0	126.0	127.0
4			136.0	126.0	127.5
$\bar{x}$	128.6	128.0	130.4	126.0	127.8
S	2.08	1.0	4.19	1.08	1.10

* - 50 mL of the suspension was centrifuged at 1.6×10^4 rpm for 30 min.

** - 150 mL of the suspension was centrifuged at 5.0×10^3 rpm for 30 min.

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ORGANIC FLUID EFFECTS ON THE STRUCTURAL STABILITY OF COMPACTED KAOLINITE

Yalcin B. Acar, Ivan Olivieri, Stephen D. Field
Department of Civil Engineering, Louisiana State University
Baton Rouge, Louisiana 70803

ABSTRACT

The effects of small particle sizes and the surface force interactions in fine grained soils are manifested by a variety of interparticle attractive and repulsive forces which strongly influence the macroscopic engineering behavior and structural stability of compacted soils. This paper presents the results of studies to explain the post-constructional behavior of compacted soils in terms of the properties of the individual components of the system. Since organic leachates are of immediate concern, the static dielectric properties of the pore fluid and the activity of the soil are emphasized.

The results of permeability and pore size distribution studies indicate that changes in hydraulic conductivity with organic fluids are due to variations in the surface forces of interaction. These changes in the interaction forces are well reflected with changes in the liquid limit and free swell of kaolinite. It is suggested that such simple classification tests with the leachate be used to obtain a qualitative estimation of the expected changes in hydraulic conductivity of a soil.

INTRODUCTION

Containment of wastes with different organic and inorganic constituents in shallow land waste disposal facilities has stimulated the study of leachate effects on the engineering properties of compacted soil liners. Presently, highly active (activity is defined as the plasticity index divided by the percent finer than -2 μm by weight) soils are chosen in the design of these liners. Although such a choice would render lower permeabilities (12), post-constructional changes in the chemistry of the pore fluid would alter the physico-chemical surface interactions of the fine grained fraction with high surface charge density, leading to changes in the engineering behavior. It then becomes necessary to assess whether these changes and the structural stability of the compacted soil could be estimated from a knowledge of the properties of the soil and the pore fluid.

This article presents the results of the ongoing studies on the volume change behavior and the permeability of compacted clay with reference to the present state of knowledge on the effect of variations in the forces of interaction between the minerals and the pore fluid to the engineering characteristics.

Since a majority of leachates contain a wide variety of organic constituents and recent studies indicated dramatic increases in hydraulic conductivity of compacted soils (3,6) with organic fluids, static dielectric properties of the pore fluid and the activity of the soil are emphasized.

FORCES OF INTERACTION IN FINE GRAINED SOILS

It is well established that both attractive and repulsive electrical forces exist between clay particles. Repulsive forces are primarily attributed to the interaction between diffuse double layers existing on the surfaces (10,15). The system variables that control these forces are defined in the development of the Gouy-Chapman theory of diffuse double layers. An approximate quantitative indication of the thickness of the diffuse double layer is given by (13),

$$H = f\left[\frac{DT}{h_o^2 v^2}\right]^n \qquad (1)$$

where H = relative thickness of double layer, D = dielectric constant of the medium, T = temperature, h_o = electrolyte concentration, v = cation valence, and n = a constant ($\approx\frac{1}{2}$). Hence, changes in the thickness of diffuse double layer is directly related to the forces of repulsion between the clay minerals.

The principal contribution to attractive forces arise from the van der Waal's forces. The van der Waal's forces could either be ion-dipole or dipole-dipole interactions. Other factors that contribute to attractive forces are Coulombic attractions between negative surfaces and positive edges, cation linkages and hydrogen bondings (10,11). It should be noted that attractive forces are insensitive to slight variations in the chemistry of the pore fluid.

Moore and Mitchell (14) developed analytical expressions for both electrostatic and electrodynamic forces of interaction between particles. The expressions developed indicate these forces of interaction are functions of the static dielectric constant of the pore fluid. Figure 1 presents the changes in these forces with variations in the dielectric constant of the medium. As it is observed the net forces of interaction closely follow the Van der Waal's attraction curve with minimum attraction at approximately a static dielectric constant of 4.0 which represents the dielectric constant of the clay particles. In order to evaluate the applicability of their theory, Moore and Mitchell (14) conducted vane shear and triaxial tests on resedimented Georgia kaolinite after permeating miscible organic fluids of variable dielectric constants. The sample volume was kept constant during this permeation. The relationships between the strength and the dielectric constant confirmed the hypothesis exhibiting shapes corresponding to the net interaction curve in Figure 1.

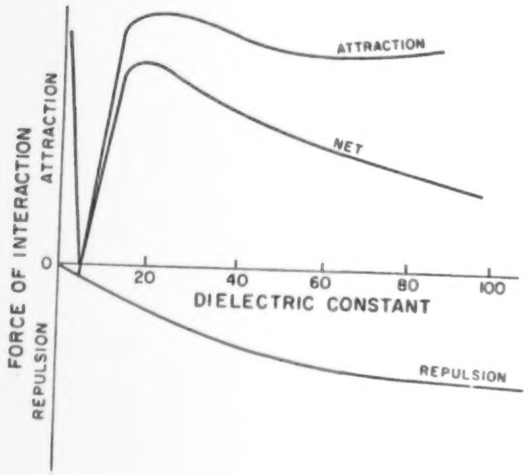

Figure 1. Forces of Interaction on Clay Surfaces (14).

The above discussion indicates that permeating an organic fluid through compacted soils would change the forces of repulsion and reestablish the net forces of interaction in the fine grained fraction leading to changes in the microfabric and the macroscopic engineering behavior. Since forces of repulsion are also a function of the surface charge density, minerals with a higher surface charge density (smectitic minerals) will be affected to a higher degree with these changes. In order to assess and quantify the changes in volume change behavior and permeability of compacted soils, an experimental procedure is implemented where the surface charge density and dielectric constant of the pore fluid were taken as the variables.

EXPERIMENTAL PROCEDURE

Kaolinite and Ca-montmorillonite are chosen for permeation studies. For index properties and free swell tests Na-montmorillonite is also used. The mineralogical composition, index properties and compaction parameters of kaolinite, Ca-montmorillonite and Na-montmorillonite are presented in Table 1. Organic fluids representing a wide range of dielectric constants were used. Table 2 presents the characteristics of various compounds used in this study together with their hazard classification and maximum reported concentration in leachates collected from waste disposal facilities (16).

TABLE 1. COMPOSITION AND CHARACTERISTICS OF CLAYS USED IN THIS STUDY

Characteristic	K	Ca-M	Na-M
Mineralogical Composition (% by weight)			
Kaolinite	98	--	--
Illite	2	8	T
Ca-Montmorillonite	--	92	--
Na-Montmorillonite	--	--	100
Index Properties (%)			
Liquid Limit	64	88	425
Plastic Limit	34	54	58
Plasticity Index	30	34	367
Specific Gravity	2.65	2.70	2.70
% Finer than 2 m size	90	12	80
Activity	0.32	2.8	4.5
Proctor Compaction Parameters			
Maximum Dry Density (t/m^3)	1.37	1.15	1.15
Optimum Water Content (%)	31.0	25	25

K - Georgia Kaolinite
Ca-M - Ca-Montmorillonite
Na-M - Na-Montmorillonite
T - Trace Quantity

TABLE 2. CHARACTERISTICS OF ORGANIC SOLVENTS (1)

Compound	Formula	ε	μ	γ	DM	pH	Class	Max Conc. (mg/1)	SBL (gm/1 at 25°C)
Water	H_2O	80.4	1.0	.98	1.83	7.0	-	-	-
Ethylene Glycol	$C_2H_6O_2$	38.66	21.0	1.11	2.2	6.4	-	-	∞
Nitrobenzene	$C_6H_5NO_2$	35.74	2.03	1.20	4.22	3.9	H,T,S,P	0.74	1.90
Acetone	C_3H_6O	20.7	0.33	0.79	1.66	6.8	T	42.4	∞
Phenol	C_6H_6O	13.13	12.7	1.06	1.45	3.5	H,T,P,S	17.0	86.34
Aniline	$C_6H_5NH_2$	6.9	4.40	1.02	1.55	9.9	T,S	1.9	34.0
Xylene	C_8H_{10}	2.50	.81	.87	0.40	5.6	T,S	60	.20
Benzene	C_6H_6	2.28	0.65	0.88	0	5.7	H,T,P,S,	7.4	1.77
P-Dioxane	$C_4H_8O_2$	2.21	1.44	1.03	.45	5.8	H,T	-	∞
Heptane	C_4H_{16}	1.0	.41	.68	0	5.4	-	-	.003

ε - dielectric constant (20°C)

γ - unit weight (gm/cm^3) (20°C)

μ - viscosity (centipoises) (20°C)

DM - dipole moment (debyes)

Class. - Hazard classification [16]

H - hazardous
S - section 311 compound
T - toxic
P - priority pollutant

Max Conc. - maximum concentration reported in leachates (mg/1)

SBL - water solubility

Permeability Tests

Permeability tests are conducted in flexible wall permeameters. The results are also compared with tests in rigid wall permeameters. Mercury intrusion tests were performed on the samples before and after permeation with the organic fluids. The details of the test setup and testing procedure are presented elsewhere (1,2). Presently, tests with kaolinite are completed.

Atterberg Limits

In order to determine the effect of organic fluids on the liquid limit and hence the repulsive forces in the clays, Casagrande apparatus was first used. It was then realized that this apparatus gave inconsistent results with organic fluids of low dielectric constants. This was mainly due to the fact that as the plasticity index of the clay mineral decreased, the shear failure was mobilized at the interface between the soil and the brass cup resulting in uncomparable liquid limit values. In order to avoid this discrepancy, Swedish fall cone tests were used (6).

Free Swell Tests

Free swell tests is another method of determining the repulsive forces between the clay particles. The free swell test is performed by pouring 10 cc of dry soil, passing No. 40 sieve into a 100 cc graduate cylinder filled with the liquid. The final swelled volume is recorded after the suspension came to rest. Free swell (F.S.) is given by

$$\text{F.S.} = \frac{V_b - V_o}{V_o} \times 100\% \qquad (2)$$

where V_b = soil volume after swelling and V_o = soil volume before swelling. This procedure is often used in the classification of soils for swelling potential.

ANALYSIS OF RESULTS

The results of permeability tests with four pure organic fluids and compacted kaolinite are presented in Figure 2. Dramatic increases experienced in previous studies with rigid wall permeameters (3,6) were attributed to side leakages (1). Tests with nitrobenzene

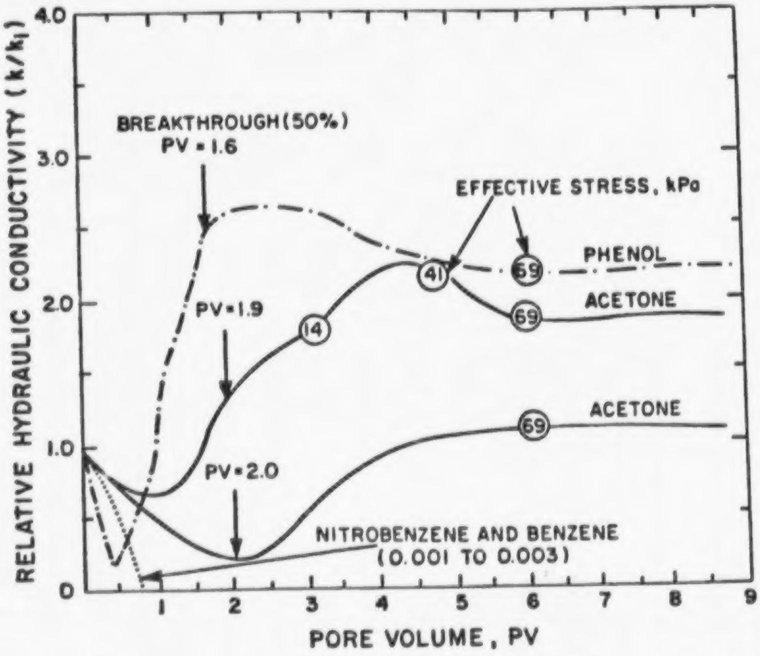

Figure 2. Hydraulic Conductivity of Compacted Kaolinite to Pure Fluids (1).

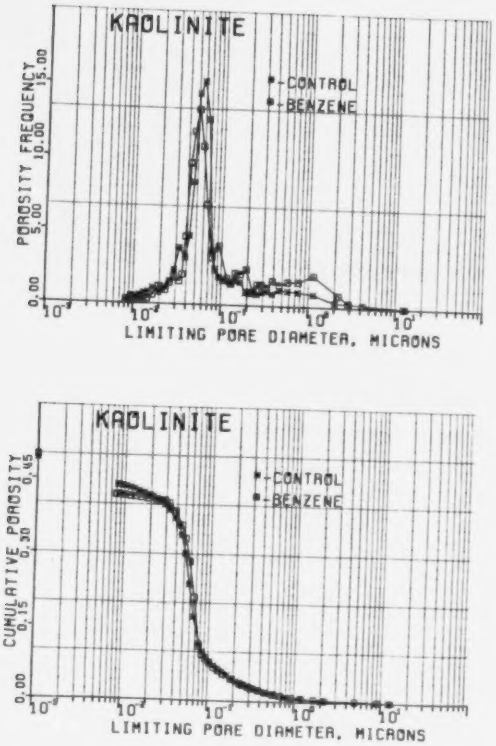

Figure 3. Pore Size Distributions of Compacted Koalinite Before and After Permeation with Benzene.

and benzene resulted in three orders of magnitude decrease in relative permeabilities, while acetone and phenol result in up to one-fold increase. Table 3 compares the final mean relative and absolute permeabilities with pure organic solvents and the 0.01 N $CaSO_4$ solution.

Figure 3 compares the pore size distribution of compacted samples before and after permeation with benzene. Cumulative porosity distributions indicate that major changes are not observed. The mercury intrusion method scans pores of 80 A° or greater and the modal pore diameter for these samples is 600 A°. It is then expected that the majority of flow is through pores of 600 A°.

Figure 4 plots the pore size parameters obtained from the distribution analysis with respect to absolute permeability (4). It is observed that pore size parameters do not respond to variations in absolute permeability. Consequently, two explanations could be given for the change in hydraulic conductivity; plugging or unplugging of pores due to particle migrations or unusual properties of the pore fluid close to clay surfaces.

Non-Darcian type of flow through compacted soils have previously been demonstrated to be caused by particle

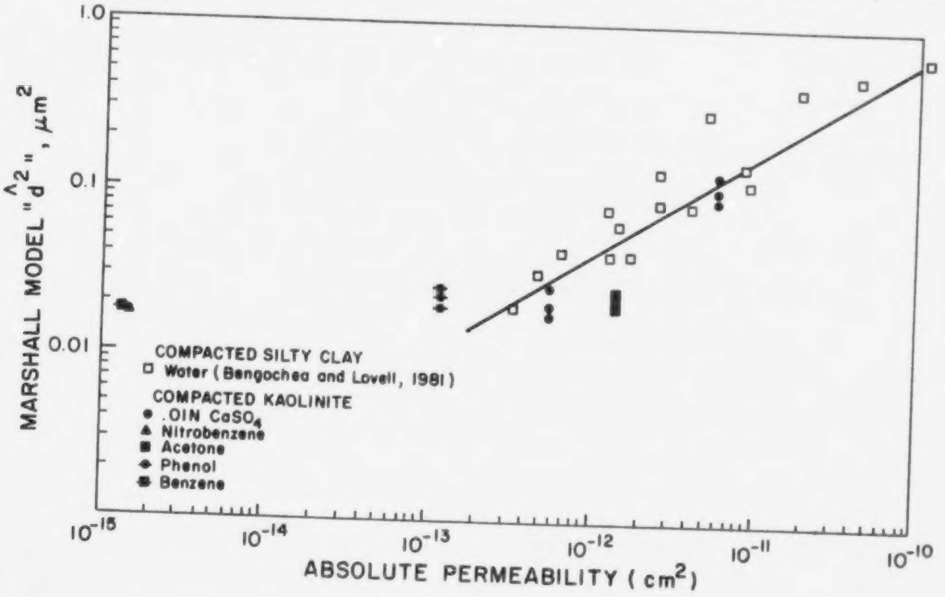

Figure 4. Correlation of Marshall Model Parameter with Absolute Permeability (2).

TABLE 3. A COMPARISON OF RELATIVE AND ABSOLUTE PERMEABILITY OF COMPACTED KAOLINITE (1)

Permeant	Permeability				
	Relative $\times 10^{-8}$ cm/sec		Absolute $\times 10^{-15}$ cm^2		
	k_i*	k_f	K_i	K_f	K_f/K_i
Nitrobenzene (1)	5.60	0.025	560	1.51	2.7×10^{-3}
(2)	5.20	0.015	520	0.91	1.8×10^{-3}
Acetone (1)	5.60	6.00	560	1470	2.63
(2)**	5.00	11.00	500	2690	5.38
Phenol	6.00	14.00	600	119.0	0.20
Benzene	5.10	0.010	510	1.38	2.7×10^{-3}

*Initial permeabilities with 0.01 N $CaSO_4$

**Test at effective stress of 13.8 kPa (2 psi)

$K = k\mu/\gamma$

γ = unit weight of permeant

μ = viscosity of permeant

migrations (8). It is also possible to initiate such a mechanism by changes in the forces of interaction. The increase in dispersive forces might tend to dislocate particles. There exists contradicting information on whether the unusual pore fluid properties around clay particles effect the fluid flow through fine grained soils (13). However, if the properties of the pore fluid in the diffuse layer around the clay particles are different than that of water, the changes in the thickness of this layer will result in variations in the effective pore space contributing to the total flow.

Since the extent of repulsive forces is related to the thickness of the diffuse double layer and the liquid limit values and free swell tests present a good estimate of this thickness (12), such tests were conducted on the clays with the organic fluids used in this study. As presented in Figures 5 and 6, dielectric constant correlates with both the liquid limit and free swell of the smectitic minerals. However, kaolinite did not follow this trend; the liquid limit and free swell is increased with nitrobenzene, and benzene slightly increased with phenol and decreased with acetone. Such observations are possible in low active kaolinite minerals since the unaccounted charges at the broken edges of this mineral have a major effect on the forces of interaction.

If the liquid limit and free swell of a soil with any pore fluid increases when compared to that of water, this implies a corresponding increase in the thickness of the diffuse layer. Considering that this thickness might extend to 400 A° with water and that the modal pore diameter of 600 A° and the frequency are not changed with organic fluid permeation indicate that the variations in the forces of interaction on the clay surface would be the major factor affecting the flow. In fact the changes in liquid limit and free swell are consistent with absolute permeability values presented in Table 3. An increase in the liquid limit and free swell with nitrobenzene and benzene shows that repulsive forces and the thickness of diffuse layer is increased resulting in a decrease in permeability (1). The reverse mechanism would be true for acetone.

If the results of the permeability and pore size distribution tests with Ca-montmorillonite are consistent with the conclusions reached using kaolinite as reported herein, the case for using simple classification tests with a specific leachate to provide an initial qualitative estimate of changes to be expected in hydraulic conductivity will be greatly strengthened.

CONCLUSIONS

The present results of ongoing studies are summarized as:

1. Organic fluid permeation does not affect the size and distribution of pores in kaolinite samples compacted at the wet of optimum water content.

2. Three order of magnitude change in hydraulic conductivity at the same pore size distribution indicate that these changes are initiated by changes in the surface forces of interaction on clay surfaces.

3. The liquid limit and free swell of sodium or calcium-saturated montmorillonite appear to be strongly related to the dielectric constant of pure organic fluids. These data indicate that forces of repulsion in this mineral vary with the dielectric constant of the liquid medium.

4. The direction of changes in liquid limit and free swell of kaolinite with organic fluids is well reflected by the variations in hydraulic conductivity of compacted samples.

ACKNOWLEDGEMENT

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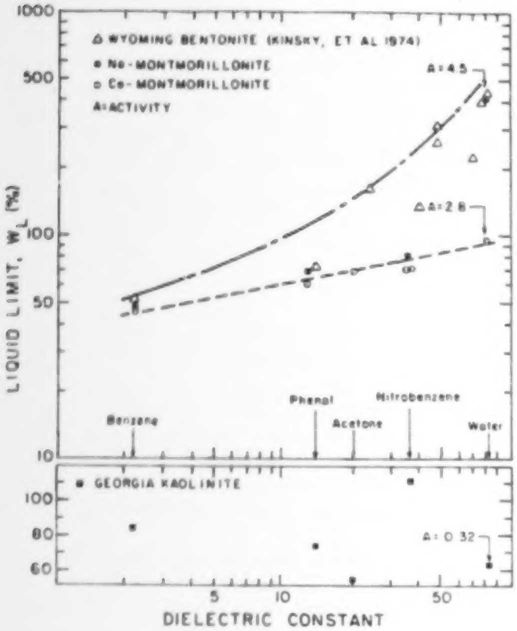

Figure 5. The Effect of Organic Fluids on the Index Properties (1).

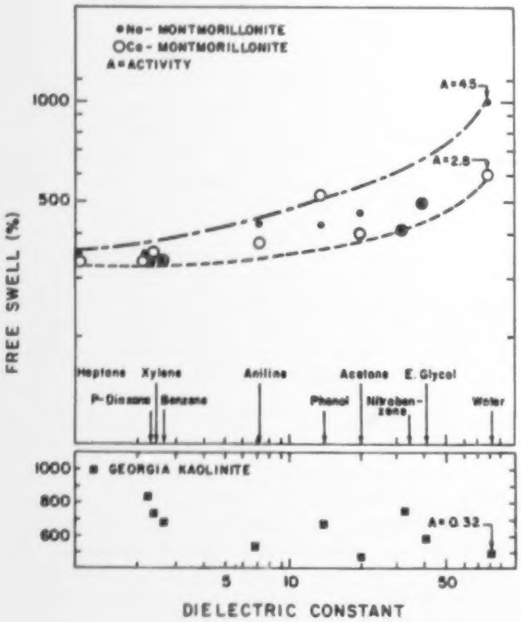

Figure 6. The Effect of Organics Fluids on Free Swell of Clays (1).

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AIR EMISSIONS OF VOLATILE ORGANIC CHEMICALS FROM LANDFILLS: A PILOT-SCALE STUDY

Louis J. Thibodeaux, Charles Springer and Guadalupe Hildebrand
College of Engineering, University of Arkansas
Fayetteville, Arkansas 72701

ABSTRACT

Through a combination of vapor phase chemical transport models and a pilot-scale simulator, volatile organic chemical emission through soils were examined. An experimental apparatus was built to simulate a landfill cell containing a liquid chemical in pure form. Models were used to determine the flux of the volatile chemical under various conditions. Two soil cover depths were investigated and carbon dioxide was used as a landfill gas purge. The landfill gas purge and cover depths had varying effects on the ability of the volatile chemical to diffuse through the soil layer, dependent upon the volatile chemical used. This paper discusses the changes of chemical flux rates of selected chemicals and compares the model prediction to experimental results.

INTRODUCTION

Burial pits and landfills have been classified as near-surface impoundments. Such land depositories have been and will undoubtly continue to be disposal sites for solid and chemical wastes. Hazardous substances are known to have escaped the sites in liquid form and as water leachate and these emissions have been studied extensively with the result that a broad base of technical knowledge exists on this subject. However, until recently, aspects of vapor-phase emissions have been given little study.

The loss of chemicals to air via vapor-phase emission from landfills and land burial has been documented. Two noteworthy incidents are: the volatilization and subsequent transport by moving air currents of hexachlorobenzene (HCB) about the environment in South Louisiana (1) and the much publicized Love Canal area of Niagra Falls, NY, where analysis of air samples nearby the landfill site reveal the presence of at least 26 volatile organic compounds (3).

Purpose

The goal of this research project is to provide verified methods of estimating volatile chemical emissions into air from a variety of near-surface impoundments. The emphasis of this project is on landfills and similar subterranean structures. This goal can be achieved by a combination of model development, laboratory simulation experiments and field monitoring.

Approach

The present approach to the research project is along two parallel lines of development. One line is the procurement of data that reflect VOC emissions in a realistic landfill-type environment. This is being accomplished by use of a pilot-scale simulator. The other line of investigation is to review, evaluate, and develop vapor phase chemical transport models for the same landfill-type environment.

Pilot-scale simulator. An experimental apparatus as shown in Figure 1 was built to simulate the idealized single cell landfill containing a chemical (liquid) in pure form. The rectangular box is made of galvanized sheet metal, has an open top and dimensions of 45.7 cm (18 in.) x 45.7 cm (18 in.) x 91.4 cm (36 in.). A soil support structure consisting of a metal frame, iron grating, screen and cheesecloth, is in-place through the top to retain the soil-clay test section. The metal frame can be raised or lowered to give various soil depths. The bottom part of the apparatus contains a recording pan-evaporator. Other elements of the simulator include a small vapor circulating fan, thermocouples, gas inlet and distributor pipe, gas sample ports and a transparent access door. Another larger fan keeps the top soil surface vapor free. A silicon rubber cement is used around the metal frame, door and other entry points to assure that all vapors and decomposition gas must exit through the soil layer.

A simulation run is performed by placing a quantity of pure liquid test chemical in the pan of the evaporator. If decomposition gas purge is also being studied carbon dioxide is fed in the bottom. The entire simulator is placed in a constant temperature and humidity room. The room is vented with an exhaust fan to avoid the build up a chemical vapor and decomposition gas. Weight remaining in the pan is continuously recorded with time. The emission flux rate is computed from the weight loss rate and the area of the soil surface 2090 cm^2 (2.25 ft^2). Gas samples are withdrawn from the chamber for analysis by chromatography.

The soil presently being used has the general characteristics shown in Table 1.

Three chemical are presently being tested in the simulator. They are methanol (MeOh), methylcyclohexane (Mch) and 1,2-dichloropropane (Dcp). Table 2 summarizes properties of these chemicals. Reagent grade chemical are used in all tests.

Gas-phase transport models. Several transport models with specific application to emission of chemical vapors from landfill sources have appeared in the recent literature. Farmer, Yang and Letey (1) extend Fick's first law for the diffusion of chemical through a porous media. The effective diffusion coefficient is a function of the molecular diffusivity of the chemical, the air filled porosity and the total soil porosity. The model is tested with hexachlorobenzene waste.

Thibodeaux (4) extends the Fickian transport model to include the effect of decomposition gas flowing through the cap to enhance the vapor transport. Mathematical simulations with benzene, chloroform, vinyl chloride and PCB suggest that bio-gas purge can enhance the volatile chemical emission rate by a factor of seven. An effective diffusion coefficient based on field measurements of radon ($^{222}R_n$) and Farmers, et. al. hexachlorobenzene data was used to establish the general creditability of the model.

The model was extended (5) to consider the dynamics of the landfill environment. Landfill decomposition gas dynamics and flow were simulated to account for barometric pressure effects on emission. Based on in-situ gas permeability measurements in a waste trench containing tritium, seasonal cap permeabilities and seasonal emission rates of benzene were computed. The fluctuation of the barometric pressure was found to increase the emission rate by 13% as compared to constant pressure conditions. A sensativity analysis of the effect of season, cover thickness, cell porosity, cell depth, and decomposition gas generation rate on emission of benzene was also performed.

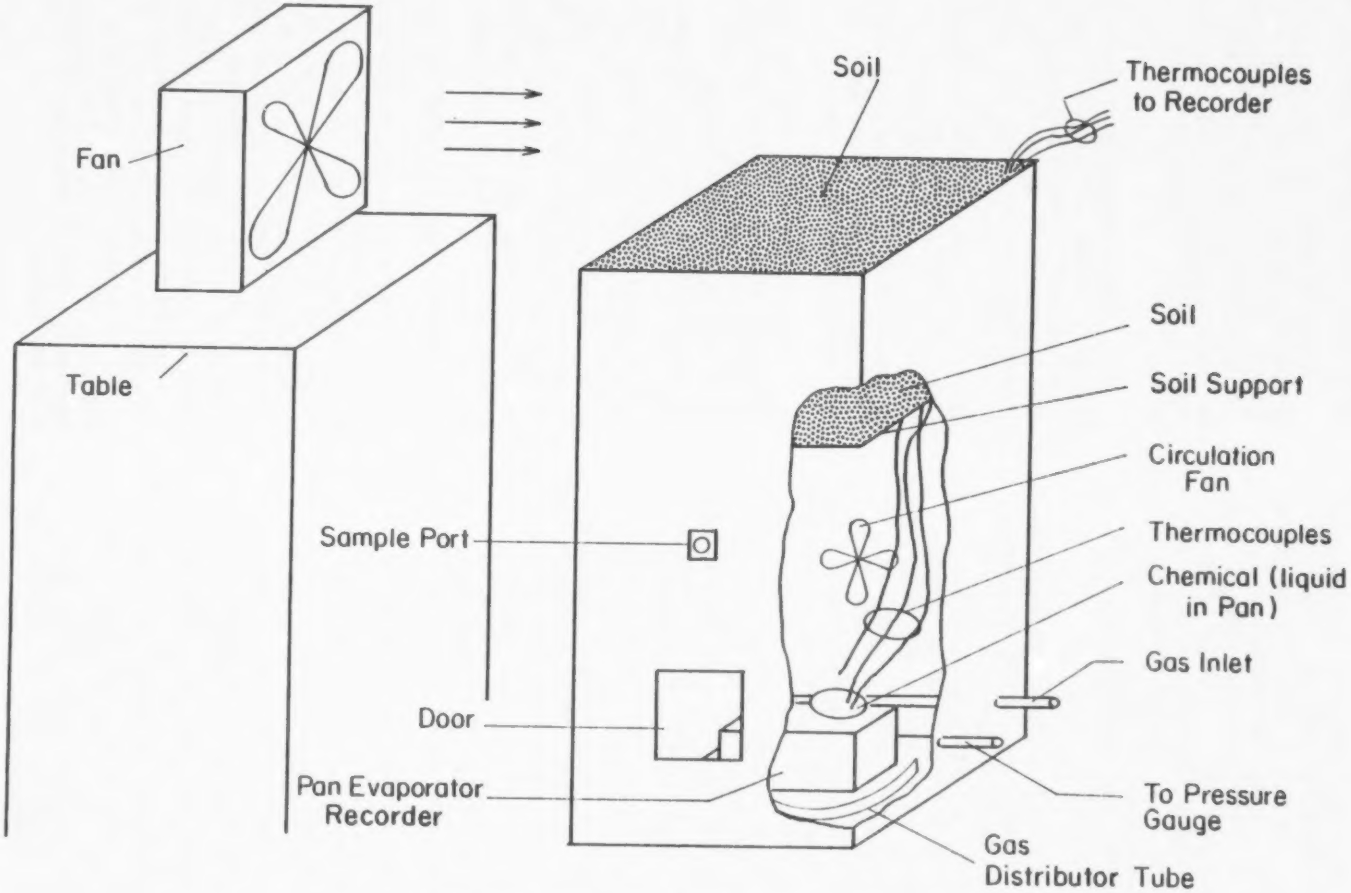

Figure 1. Landfill Simulator Apparatus

Murphy (2) presented a model for volatiles diffusing through the bulk waste, through the soil and then into the lower atmosphere boundary layer. A time dependent rate equation is presented inasmuch as the flux into the atmosphere decreases the amount of volatile chemical in the waste and increases the transport distance. The model equations are not used to make any specific prediction of emission rates.

Table 1. Soil Characteristics*

Sand Percent = 30.4
Silt Percent = 47.3
Clay Percent = 22.3
Carbon Content = 1.42%
Porosity = 0.43
Water Content = 2.43%
Bulk Density = 1.29 g/cm^3

*Analysis performed by University of Arkansas Soil Characterization Laboratory.

Table 2. Chemical Properties

Chemical	Molecular Weight	Density (g/cm^3)	Vapor 25·C Pressure (mmHg)	Water* Solubility
Methanol	32.04	$d^{15}=0.79609$ $d^{25}=0.78675$	125.03	∞
Methylcyclohexane	98.19	$d^{20}=0.76936$ $d^{25}=0.76506$	46.36	i
1,2-Dichloropropane	112.99	$d^{20}=1.5600$ $d^{25}=1.159$ Used d = 1.16 for flux calculations	50.33	δ

* ∞-soluble in all proportions
i-insoluble
δ-slightly soluble (1,2-DCP soluble 2,700 mg/l at 20·C)

Continuing study of the diffusion process in light of the volatile materials used in this study suggests that the following equation is most appropriate for interpreting the experimental results.

$$N_A = \frac{VP_AM_A}{RT}\left\{1 - P_A/PT - EXP\left[-(N_A/M_A + VP_T/RT)\ LRT/P_TD\right]\right\} \quad (1)$$

where N_A = flux of volatile chemical, $g/cm^2 \cdot s$,
V = apparent decomposition gas velocity, $cm^3/s \cdot cm^2$,
P_A = vapor pressure of the volatile, atm.
M_A = molecular weight of the volatile, g/mol,
R = gas constant 82.1 $atm \cdot mol/cm^3 \cdot K$,
T = temperature of the gas-vapor mixture, K,
P_T = atmospheric pressure, atm,
L = thickness of the soil layer, cm, and
D = effective diffusion coefficient, cm^2/s.

It should be noted that N_A also appears on the right side of the Eq. 1. This is a necessary inclussion for chemicals of high vapor pressure in the range $P_A \geq 0.05\ P_T$. An iterative scheme is required for solution of EQ. 1. For the case of no decomposition gas flowing through soil (i.e., V=0) the appropriate equation is:

$$N_A = (D\ P_T\ M_A/RTL)\ln\left[1/1 - P_A/P_T\right] \quad (2)$$

The equation can also be used to commence the iterative solution of Eq. 1.

Probelms encountered. Early experiments resulted in extremely high apparent emission rates. Values of up to 4500 $ng/cm^2 \cdot s$ for Dcp, 4100 $ng/cm^2 \cdot s$ for Mch and 3900 $ng/cm^2 \cdot s$ for Meoh were obtained through a 38.1 cm (15 in.) soil layer. Adsorption calculations suggested that the soil could be retaining quantities of the chemicals. If so this would give high apparent emission rates. It was therefore necessary to perform additional experiments to determine the extent to which adsorption occurs.

Three desiccators were used to perform chemical vapor adsorption experiments with the soil. Quantities of varying amounts of oven-dried soil were placed in 25 ml. vials. Into each desiccator was placed a sufficient amount of liquid chemical. A perforated porcelain plate was placed over the chemicl pool and the vials containing the soil were placed on top of the plate. The lids on the desiccators were sealed in-place, and the soil vials were allowed to absorb chemical vapors for approximately sixty days.

The soil samples were re-weighed and the weight change due to adsorption noted. The adsorption results were: Meoh = 0.0469 ± .0016 g/g-soil; Dcp = 0.0649 ± .0026 g/g-soil; and Mch = 0.0440 ± .0030 g/g-soil. These adsorption results indicated that it would be necessary to pretreat the soil layer with the respective chemical prior to performing emission simulations. The soil had a mass of 95.5 kg for a 38.1 cm layer and this amounted to 4.5 kg Meoh, 6.20 kg Dcp and 4.2 kg Mch sorbed.

Elaborate means of soil pre-treatment were undertaken prior to further simulation experiments. This included covering the soil surface, observing chemical and gas-vapor temperatures inside the simulator and recording the total quantity absorbed. Soil pre-treatment took up to 9 days.

A wet-test meter was used as an in-line decomposition gas flow measuring device. Moisture introduced through the meter likely interfered with some of the flux results. Water also adsorbs onto the soil and hampers chemical vapor transport. Water is soluble in Meoh. This practice was stopped and a Dri-rite filters was placed in the decomposition gas inlet lines to adsorb water vapor.

Results

During this reporting period 36 flux measurements have been completed. Three chemicals: Meoh, Dcp and Mch, and two soil layer depths: 38.1 cm and 7.62 cm have been tested. Table 3 presents the operating conditions and flux results prior to installation of the Dri-rite filter for the 38.1 cm soil depth.

liquid giving faulty readings. The experiments were repeated after installation of a moisture trap and these measurement results appear in Table 4.

The new methanol results are still inconsistent. The flux with and without decomposition gas fluctuate highly. The Dcp data show a slight increase (i.e. 6.3%) with decomposition gas purge. The Mch data show a substantial increase (i.e., 31%).

Further experiments were performed in a room with temperature and humidity control features. In addition 250 ml. aliquots of the gas from the simulator were periodically withdrawn with an evacuated gas sampling bulb and analysis performed on a Tracor 565 gas chromatograph with a flame ionization detector. The soil depth was reduced to 7.62 cm (3 in.). The results of the latest flux experiments appear in Table 5.

Table 3: Chemical Fluxes Through Soil*

Chemical	Run No.	T_{gas} (·C)	T_{liquid}(·C)	Gas Rate cm³/s	Flux ng/cm²·s
Meoh	1	23.4	19.9	0.0	525
Meoh	2	20.4	17.8	0.0	472
Meoh	3	19.9	17.9	2.05	444
Meoh	4	21.7	19.7	2.05	472
Dcp	5	20.0	19.0	0.0	1445
Dcp	6	20.0	19.2	0.0	1651
Dcp	7	22.0	21.0	2.03	1541
Dcp	8	21.0	20.9	2.03	1581

*Soil Depth: ~ 38.1 cm, w/o Dri-Rite

As is evident from the results in Table 3, there is essentially no difference between the flux with and without decomposition gas flow. The introduction of high moisture levels appears to have been influencing the process. Water can adsorb on the soil and into the pan

Gas analysis results, available only on runs 21 through 33 indicate that the gas below the soil bottom surface in the simulator is not saturated with chemical vapor. Comparison with the pure component vapor pressure at the temperature of the liquid indicate the partial pressure of Meoh is

Table 4. Chemical Fluxes Through Soil*

Chemical	Run No.	T_{gas} (·C)	Tliquid(·C)	Gas Rate cm/s	Flux ng/cm^2·s
Meoh	9	23.8	20.8	0.0	1046
Meoh	10	25.5	22.5	0.0	923
Meoh	11	24.5	22.0	1.90	1328
Meoh	12	23.8	20.8	1.90	701
Dcp	13	22.3	21.2	0.0	2240
Dcp	14	23.1	21.8	0.0	2340
Dcp	15	23.4	22.0	1.90	2470
Dcp	16	26.0	24.5	1.90	2400
Mch	17	24.4	22.5	0.0	1146
Mch	18	23.6	21.7	0.0	1167
Mch	19	23.6	21.6	1.90	1556
Mch	20	25.0	23.1	1.90	1474

*Dri-Rite Filter in Place, Soil Depth: 38.1 cm

Table 5: Chemical Fluxes Through Soil*

Chemical	Run No.	T_{gas} (·C)	T_{liquid}(·C)	Gas Rate cm/s	Flux ng/cm^2·s
Meoh	21	17.6	12.5	0.0	909
Meoh	22	17.4	12.0	0.0	911
Meoh	23	17.6	12.5	0.0	910
Meoh	24	17.8	13.2	0.0	984
Meoh	25	17.2	13.4	0.0	978
Meoh	26	17.4	13.6	0.0	883
Meoh	27	17.8	13.0	0.0	895
Meoh	28	17.2	12.8	5.70	1192
Meoh	29	16.8	13.4	5.70	1195
Meoh	30	16.5	12.7	5.70	1203
Dcp	31	17.4	15.7	0.0	1432
Dcp	32	17.5	15.9	0.0	1436
Dcp	33	16.8	15.3	0.0	1436
Dcp	34	17.0	15.7	0.0	1441
Dcp	35	17.5	16.1	0.0	1444
Dcp	36	17.3	15.6	0.0	1453

*Dri-Rite Filter in Place, Soil Depth 7.62 cm

51.6% (σ=6.666%) saturated for no decomposition gas and 66.1% (σ=2.76%) saturated with gas. Dcp with no gas was 61.6% (σ=3.55%) of saturation. Measurements with Mch are incomplete at this time.

The chemical flux rates of Meoh appear to be significantly enhanced with purge gas flow. The data in Table 5 indicate an average of 29% increase in the flux. Temperature variations preclude a comparison of the effect of decreased soil depth on flux in Table 5 from that in Tables 3 and 4.

The extraction of the effective diffusion coefficients from the raw data provides an additional parameter to interpret the results. These values also provide a means of translating the laboratory data to field conditions. This has been performed by solving Eq. 1 for D and using the laboratory data for N_A, P_A, L, etc. The effective diffusion coefficients appear in Table 6.

The mean values for methanol are .253 (σ=.105)cm^2/s for the 38.1 cm. soil depth and .115(σ=.0169)cm^2/s for the 7.62 cm. soil depth. The dichloropropane values are .445(σ=.0807) and .085(σ=.00488)cm^2/s respectively. The methylcyclohexane apparent diffusion coefficient for the 38.1cm soil is .349(σ=.0462)cm^2/s. In general these deep soil values are higher than the molecular vapor diffusivities (i.e., .051 to .17 cm^2/s). The 7.62 cm soil depth apparent diffusion coefficients are in general slightly less than the molecular vapor diffusivities. Diffusivities were estimated using the Wilke-Lee modification of the Hirschfelder-Bird-Spotz method (6).

The results presented here are based on limited data so no conclusions will be drawn at this point.

Acknowledgement

Mr. Stephen C. James is the Project Officer for this research endeavor. His continuing interest in this subject and his technical input create a stimulating atmosphere for inquiry. Vicki Welytok and Phil Lunney are acknowledged for helping with the chemical analysis of the gas samples.

Table 6. Effective Diffusion Coefficients*

Meoh Run No.	Meoh D(cm^2/s)	Dcp Run No.	Dcp D(cm^2/s)	Mch# Run No.	Mch# D(cm^2/s)
1	.229	5	.371	17	.345
2	.230	6	.420	18	.259
3	.147	7	.342	19	.463
4	.142	8	.352	20	.407
9	.435	13	.520		
10	.351	14	.558		
11	.382	15	.535		
12	.207	16	.462		
21	.142	31	.0923		
22	.146	32	.0861		
23	.116	33	.0855		
24	.107	34	.0886		
25	.119	35	.0776		
26	.0892	36	.0805		
27	.112				
28	.113				
29	.0982				
30	.104				

* Top half of table for 38.1 cm soil, lower for 7.62 cm soil depth
# Assumed 60% vapor saturation.

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ASSESSMENT OF SURFACE IMPOUNDMENT TECHNOLOGY

By
Masood Ghassemi, Michael Haro, and Linda Fargo

MEESA
18811 Crenshaw Place, Suite 201
Torrance, CA 90504

ABSTRACT

Case studies of hazardous waste surface impoundments (SI) comparing actual and projected performance can contribute significantly to improving their design, construction, and operation. To this end, the available data for 22 SI's in the southwestern United States were reviewed, and six of them were assessed further for a case study. The six SI's represent a range of industries, waste types and volumes, ages, environmental settings, liner types and designs, and systems for leak detection and groundwater monitoring.

Poor performance of several ponds studied was attributed to lack of good project planning during the design and construction phase. Failure to execute proper quality assurance and control (QA/QC) procedures during the project also contributed to failure of these ponds. Deviations from desired liner specifications and poor liner-waste compatibility testing resulted in poor performance. At at least one site studied, poor impoundment performance resulted from the lack of rigorous site-specific investigations to develop the basis for proper design and construction.

The successful performance of SI's at one facility is attributable to (1) use of a very impermeable clay as liner material after extensive waste-liner permeability studies, (2) use of competent design, construction, and inspection contractors, (3) close scrutiny of all phases of design, construction, and QA inspection by the owner/operator, (4) excellent QA/QC and record keeping during all phases of the project, and (5) good communication between all parties involved in establishing the SI's.

INTRODUCTION

The Solid and Hazardous Waste Research Division (SHWRD) of EPA's Municipal Environmental Research Laboratory (MERL, Cincinnati, OH) is investigating the use of surface impoundments (SI's) for hazardous waste management. The primary aims of this research are to develop criteria for improved SI design and operation and to provide technical support to EPA's Office of Solid Waste in developing SI regulations according to the provisions of the Resource Conservation and Recovery Act (RCRA).

Currently, the principal source of EPA information on hazardous waste surface impoundments is the Surface Impoundment Assessment (SIA) data base developed by the Office of Drinking Water. Though the data base contains some background survey information on the numbers, types, and uses of wastes handled by municipal, industrial, and agricultural SI's in the United States, it contains little or no information on their engineering design and actual performance. Comparison of projected and actual performances at operating SI's and identification of reasons for observed differences are essential for designing better new SI's and for formulating appropriate corrective actions at existing sites.

PURPOSE

The purpose of the present study is to develop a data base on hazardous waste surface impoundment design and operating practices and to compare actual and projected performance for a selected number of facilities. The study will identify gaps in the existing data base and areas that most warrant research and development.

APPROACH

Two complementary approaches are being used to define the state-of-the-art for hazardous waste surface impoundment technology: (a) case studies for a selected number of SI's, and (b) interviews with technical experts.

CASE STUDIES

The SI's for the case studies were selected largely from those operating in the southwestern United States, primarily California and Texas. In selecting specific impoundments, the following data sources were consulted:

- State data files for CA, TX, UT, NM, and AZ.
- State Surface Impoundment Assessment (SIA) surveys.
- Background information collected and analyzed recently for a number of hazardous waste management facilities in connection with several recent projects sponsored by the Land Disposal Branch of EPA's Office of Solid Waste, including "Risk Assessment for RCRA Subtitle C Land Disposal Regulations and Regulatory Impact Analysis," "Preparation of Background Information on Hazardous Waste Management Facilities," "Assessment of Technology for Constructing and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities," and "Waste Stream Description and Categorization."

Twenty-two facilities were selected as potential candidates for case studies based on consultations with the above data sources. These sites were further screened by means of exploratory discussions with state regulatory agencies and facility owners/operators, and the following factors:

- Amount of data available
- Representation of a range of SI service types

- Type of liner (including no liner) used

- Types of hazardous waste handled

- Design and construction practices used

- Facility performance

- Absence of litigation

- Anticipated level of cooperation from owner/ operator

The prelimary screening eliminated eight sites (Table 1) from further consideration. These sites were rejected because of multiple potential sources of pollution (three), ongoing litigation (two sites), and lack of operating data because of the newness of the sites (two sites). The previously collected data on the remaining 14 sites were then supplemented with additional data obtained from state agencies, owners and operators and used to prepare detailed assessments for these sites. As a result, eight additional sites were eliminated and detailed case study and assessment summary reports were prepared for the remaining six sites.

Table 2 presents background information on eight facilities that were subjected to detailed evaluation and rejected as unsuitable for the case studies, primary reasons for rejection are included. As noted in Table 2, these sites were generally found unsuitable for performance analysis because of the absence or lack of adequate monitoring data (Facility A), multiple potential sources of contamination (Facilities B and D), recent changes in operating practice that eliminated discharge of hazardous waste to pond (Facility C), refusal of the owner or operator to participate in the study (Facilities E, F, and G), and discovery of the unsuitability of the site after more detailed analysis (Facility H).

Tables 3, 4, and 5 present the information on the six cases that were evaluated in some detail and for which case study and assessment summary reports were prepared. Table 3 contains general information on these sites, including the types and qualities of wastes handled. As noted in the table, these SI's serve a variety of industries, handle different waste types and volumes, are used for disposal or treatment purposes, and range in age from less than 2 to more than 30 years. Some general information on the environmental setting (surrounding land use, geology, and hydrology) for the SI's is presented in Table 4 to indicate the spectrum of conditions represented by the sites considered. The SI technology information on the sites appears in Table 5. The case studies cover a range of liner types and designs (single versus double liner, clay versus Flexible Membrane Liners (FML) versus clay and FML) and leak detection systems. The extent of groundwater monitoring also varies from use of no observation wells to use of multiple wells at strategic locations.

The case study report prepared for a site is essentially a compilation of all available relevant data for that site and is the basis for performance assessment. Depending on the number of data available, the report contains some or all of the information categories shown in Table 6. For each facility, the draft case study report was submitted to the site owners/operators for review to assure accuracy and completeness and to provide them with an opportunity to expand or supply additional information or clarification on the various topics covered. In transmitting the draft reports, the owners/operators were requested to provide any quantitative engineering data (e.g., on the original site design, actual construction, liner inspection/ maintenance programs, etc.) that might support some of the qualitative statements and assertions. Comments received from the reviewers were incorporated in the case study reports as appropriate.

TABLE 1. FACILITIES ELIMINATED FROM FURTHER CONSIDERATION IN THE PRELIMINARY SCREENING

Facility	Waste Type	Liner Type	Leak Detection	Groundwater Monitoring	Basis for Elimination
Commercial hazardous waste disposal facility	Various industrial hazardous wastes	Various FMLs*	Yes	Yes	Company involved in litigation with the state
Agricultural chemical formulation facility	Pesticide rinse-waters	Bentonite	No	Yes	The system placed in service only recently
Aircraft manufacturing facility	Various hazardous wastes	PVC	No	Yes	Possible Superfund litigation
Commercial hazardous waste disposal facility	Petroleum and chemical industry wastes	In-situ clay	No	Yes	SI performance difficult to evaluate because of other technologies (landfills and land farming) on site
Aircraft/Aerospace manufacturing	Various hazardous wastes	FML	Yes	Yes	SI operation began very recently (Spring 1983)
Circuit board manufacturer	Metal wastes	FML	No	No data	Plant closed down
Commercial hazardous waste disposal facility	Various industrial wastes	Clay	No	Yes	Other technologies (landfills and land farming) located on site
Sulfuric acid plant	Acidic wastes	FML	No	Yes	Facility built on waste piles from an abandoned copper smelting operation

*Flexible Membrane Liners

TABLE 2. FACILITIES EVALUATED BUT REJECTED AS CASE STUDY SITES

Facility Designation	Facility Type	Waste Type	Liner Type	Leak Detection	Groundwater Monitoring	Primary Reason for Rejection
A	Hydro-metallurgical processing plant	Acid wastes	30-mil reinforced Hypalon	No	Yes	SI performance could not be evaluated because the groundwater monitoring system was just installed
B	Olive processing plant	Brines	Double-lined with 10-mil Polyethylene sheets; liners separated by 2 ft of sand on side slopes and 1 ft of sand on the bottom	Yes	No	Irrigation water from adjacent lands influencing leak monitors
C	Chemical manufacturing plant	Acid wastes with heavy metals content	Butyl rubber	No	Yes	The owner/operator declined to participate in the study indicating that no hazardous waste has been received since new liners were installed in mid-1982, and the SIs currently contain no hazardous liquids or solids
D	Copper products	Acidic metal-treating wastes	CPE placed on 12 inches of clay and 12 inches of sand	Yes	No	This site is located adjacent to site for Case Study No. 1 and has the same general design and operating history and hydrogeological characteristics. Inclusion of this facility as a full case study was considered to bias the sample of facilities studied in the program
E	Copper smelter	Acidic metal-bearing wastes	Hypalon	Yes	Yes	The owner/operator declined to participate in the study and there was not enough data available from other sources
F	Electroplating facility	Electroplating sludges	HDPE*	No	Yes	The owner/operator declined to participate in the study and there was not adequate data available from other sources
G	Oil refinery	API separator sludge	Soil asphalt	No	Yes	The owner/operator declined to participate in the study and there was not adequate data available from other sources
H	Chemical plant	Corrosive, caustic wastes	CPE+	Yes	Yes	The FML≠ is underlain by reinforced concrete; the system is thus more of a container than a SI

***High-density polyethylene**
+Chorinated polyethylene
≠Flexible Membrane Liners

TABLE 3. CASE STUDY FACILITIES - GENERAL FEATURES AND WASTE CHARACTERISTICS

Case Study No.	Type of Facility	Type of SI (No. and Function)	Year SI Placed In Service	SI Size (Acres)	Waste Type	Waste Quantity
1.	Electrolytic metal refining plant	Small disposal pond	1972	0.4	Acidic process liquor and sludge waste (pH <2) high in heavy metal content	A total of 843,750 gallons in 1982
		Disposal pond	1979	1.1	Acidic process liquor and sludge waste (pH <2) high in heavy metal content	
2.	Pesticide formulation and distribution plant	Pesticide wash-down evaporation disposal pond	1979	<0.1	Pesticide rinsewater	Batch operation (400 gallons/day maximum)
		Pesticide rinse-water evaporation disposal pond	1982	<0.1	" " "	" "
3.	Commercial hazardous waste disposal facility	Site A: 8 impoundments used for settling, storage, and sludge disposal	1951	15	Oily water and brines, alkaline and acid wastes, heavy metals, paint sludge, tank bottom sediments, cyanide, pesticides, and other chemical wastes	A total of 53,000,000 gallons in 1982
		Site B: 7 evaporation disposal ponds	1971	74	" " "	
4.	Agricultural fertilizer manufacturing plant	11 settling ponds used to recover gypsum	1965	14	Production water from ammonium phosphate/phosphoric acid plant with pH <2 and high radionuclides content	20,000 gallons/day
		One evaporation pond (treatment)	1976	8	Wastewaters from plant boilers, water treaters, and nitric and sulfuric acid plants (pH <2, high in radionuclides)	130,000 gallons/day
		One cooling pond (treatment)	1976	38	Same as gypsum SIs	10,000 gallons/day

(Continued)

TABLE 3. (Continued)

Case Study No.	Type of Facility	Type of SI (No. and Function)	Year SI Placed in Service	SI Size (Acres)	Waste Type	Waste Quantity
5.	Borate and boric acid mining/manufacturing plant	5 low-head solar ponds (disposal)	1972	90	Borate liquor tailings with high arsenic and boron content	A total of 50,000,000 gallons/month to Ponds A-E, 4, and 5
		High-head evaporation pond (disposal)	1975	80	" " "	
		High-head evaporation pond (disposal)	1976	100	" " "	
		Evaporation pond (disposal)	1980	120	Boric acid plant wastewater with high arsenic and boron content	12,000,000 gallons/month
6.	Commercial hazardous waste disposal facility	Evaporation pond (disposal)	1980	5	Geothermal muds and brines, wastewater treatment sludge, tank bottom sediments, cooling tower blowdown sludge and oil drilling muds	9,850,000 gallons in 1981
		Disposal pond (currently used for land treatment)	1980	5	" " "	
		Disposal pond (currently used for land treatment)	1981	5	" " "	

TABLE 4. CASE STUDY FACILITIES - ENVIRONMENTAL FEATURES

Case Study No.	General Setting	Geology	Hydrology	Other Nearby Potential Sources of Pollurion
1.	Desert region of the Southwest. The area heavily industrialized with several major hazardous waste generators adjacent to the plant.	An alakline, loamy fine sand extending about 70 feet beneath the site and having a permeability of 10^{-2} cm/sec. Also beneath the site are a few thin clay and silt lenses.	Rainfall averages 8.8 inches annually. A complex groundwater system, consisting of a water table aquifer (80 feet beneath the site) and a semi-confined aquifer, underlies the facility. The upper aquifer recharges the lower one which is the principal source of municipal and industrial water in the area.	On-site bentonite-lined cooling ponds. Abandoned (1972) unlined wastewater pond. Evaporation ponds adjacent to this site.
2.	An alluvial valley of the Southwestern U.S. Nearby land uses include agriculture, commercial, and residential.	No data.	No data.	None.
3.	Surrounding lands are marshy, and nearby land uses include solid waste disposal and flood control.	Site A underlain by 150 to 700 feet of organic clays (permeability ranges from 10^{-5} to 10^{-8} cm/sec), followed by marine sandstone and shale bedrock. Site B has 1 to 4 feet of silty clayey sands followed by 700 to 800 feet of sandy and silty clay (permeability ranges from 10^{-6} to 10^{-8} cm/sec).	Poor quality groundwater exists 3 to 5 feet below ground surface. Groundwater at Site A flows to the northeast. At Site B, the hydraulic gradient is in the form of an oval mound over the site. Groundwater is not used. The site is near a large bay and is separated from it by marshy land and flood control canals.	A commercial hazardous waste landfill immediately adjacent to Site A SIs.
4.	An alluvial valley of the Southwest. Surrounding lands are flat and are primarily for agricultural purposes.	Soil beneath the site consists of 1 to 5 feet of clay with a high calcium carbonate content followed by 150 to 200 feet of sandy soil with silt and clay lenses	Groundwater exists 30 feet below ground surface in a poorly defined perched aquifer, at 150 feet (normal water table), and at 300 to 1000 feet in a confined aquifer. Water from the perched aquifer and the unconfined aquifer is used extensively for irrigation, domestic, and industrial consumption. A small slough is located along the plant's border.	Extensive irrigation of agricultural land surrounding site. Plant wastewaters discharged to a nearby stream from 1959 to 1977. Two abandoned (1974) on-site percolation ponds.
5.	A desert region with local relief of about 15 feet.	Alluvial deposits in the vicinity consists of gravel, sand, silt, and clay. Several faults are located near the facility.	The clean sands and gravel beneath the SIs contain small amounts of groundwater at levels of about 300 feet.	None.
6.	A sparsely vegetated desert area. Adjacent lands are vacant desert.	The SIs are underlain by an ancient lake bed consisting of alternating, unweathered clay, silt, and sandy silt soils to a depth of 100 feet. Permeability ranges from 10^{-4} to 10^{-8} cm/sec.	Depths to groundwater on the eastern and western site boundaries are 30 feet and 90 feet, respectively. The groundwater is saline and is not of beneficial use in the area.	None.

TABLE 5. CASE STUDY FACILITIES - LINER AND MONITORING SYSTEMS

Case Study No.	Type of SI	Liner Type	Design/Installation Data Available	Leak Detection System	Groundwater Monitoring
1.	Small disposal pond	Originally lined with a 20-mil DuPont 3110 FML; replaced in 1981 with a Goodrich 30-mil HP-6 nylon-reinforced FML.	Some data on liner design and installation available.	None.	Three wells each around the perimeter of the small and large SIs (installed in 1982) and one background well.
	Disposal pond	Hypalon.	Little data available.	None.	
2.	Pesticide wash-down evaporation disposal pond	Bottom and slopes of pond lined with 2 layers of Goodyear 30-mil PVC. Secondary liner (bottom only) is a Goodyear 30-mil PVC.	Detail drawings available (no specifications) on pond, liner, and detection system.	1-ft gravel layer and one 3-inch perforared PVC pipe extending half way across the pond and connecting to an observation well.	None.
	Pesticide rinse-water evaporation disposal pond	Primary liner is a 20-mil CPE. Secondary liner is a 10-mil PVC.	" " "	A 1-ft sand layer; a 4-inch perforated PVC pipe connected to an observation well.	None.
3.	Site A: 8 impoundments used for settling, storage, and sludge disposal	Clay.	Detailed design and construction information available for impoundment levees. Otherwise, little data available.	A subtrain trench and collection sump were installed along the eastern edge of Site A in 1971. Escaping liquids are automatically pumped back into the SIs.	Three wells.
	Site B: 7 evaporation disposal ponds	Clay	" " "	None.	14 wells around SIs.
4.	11 settling ponds used to recover gypsum	Unlined. Limited data indicate that a waste-soil seal (10^{-6} cm/sec permeability) exists beneath the ponds.	Little design/installation data available.	None.	None.
	One evaporation pond (treatment)	Lined with Pantasote 12-mil PVC on the bottom and Carlisle Tire & Rubber Co. 30-mil Dacron-reinforced EPDM on the side slopes. Secondary liner is 1-ft compacted clay.	Complete and detailed pond and liner design and construction specifications/drawings available.	Three V-ditch drains lined eith 30-mil PVC, 3-inch drain pipe, and monitoring wells.	None.
	One cooling pond (treatment)	" " "	" " "	" " "	None.

(Continued)

TABLE 5. (Continued)

Case Study No.	Type of SI	Liner Type	Design/Installation Data Available	Leak Detection System	Groundwater Monitoring
5.	Five low-head solar ponds (disposal)	10-in compacted clay.	Complete and detailed pond and liner design and construction specifications/drawings available.	None.	12 wells used to monitor groundwater in the plant vicinity.
	High-head evaporation pond (disposal)	18-in compacted clay.	" " "	A gravel collector section overlying a continuous polyethylene liner placed in a graded V-ditch connecting to a monitoring basin via a perforated pipe.	
	High-head evaporation pond (disposal)	18-in compacted clay.	" " "	" " "	
	Evaporation pond (disposal)	18-in compacted clay.	" " "	" " "	
6.	Evaporation pond (disposal)	In-situ clay with a minimum thickness of 2 feet. Recompacted clay embankments.	Some pond and liner design and construction specifications/drawings available.	None.	Four wells surrounding SIs.
	Disposal pond (currently used for land treatment)	" " "	" " "	None.	
	Disposal pond (currently used for land treatment)	" " "	" " "	None.	

TABLE 6. TYPES OF INFORMATION SOUGHT FOR THE CASE STUDIES

- Basis for site selection:
    - Geotechnical and hydrogeological considerations/studies, including results of any soil boring tests, modeling effort, and environmental impact analysis.
- Basis for selection of the design firm (and construction/installation contractors).
- Criteria used and basis for design:
    - Design objective and purpose of impoundment (disposal, storage, treatment);
    - Waste characteristics data (flow, composition, etc.);
    - Hydrogeological considerations (e.g., distance to groundwater, precipitation, evaporation, temperature, etc.);
    - Waste-liner compatibility considerations;
    - Soil permeability and leachate attenuation test results used;
    - Regulatory/permit agencies requirements;
    - Cost considerations;
    - Etc.
- Description of design and design specifications:
    - Unit size, dimensions, and configuration;
    - Liner type, characteristics, and recommendations for installation;
    - Specifications for foundation preparation, leak detection system, and liner backfill placement;
    - Inlet/outlet, aeration unit, and other appurtenances including systems for diversion of surface runoff, prevention of vandalism and animal damage;
    - Observation wells and monitoring systems;
    - QA/QC specifications;
    - Etc.
- Description of as-built facility and related matters:
    - Modifications to and deviations from the recommended design and specifications, and the basis for such modifications and deviations;
    - Problems encountered which had not been anticipated or adequately addressed in design, and mitigation measures used;
    - Level of QA/QC and competent inspection actually employed.
- Performance data and operating experience:
    - Evidence for liner/system inadequacies or failures (groundwater monitoring data and leak detection information);
    - Operating difficulties encountered and mitigation measures used;
    - The adequacy and reliability of the monitoring system to detect or forewarn problems;
    - Inspection and maintenance programs;
    - Etc.

The identity of the case study sites was of little consequence to the project objective. Thus to promote cooperation of the owners/operators, all sites were kept anonymous and are referred to only by letter or number designations.

INTERVIEW WITH EXPERTS

This phase of the effort began in September 1983 to seek expert perspective on factors affecting SI performance and deviation from design predictions. Information was sought from those most intimately involved in the design, construction, operation and regulation of hazardous waste SI's. To date, a number of individuals and organizations representing many viewpoints have been identified and contacted as possible interviewees. These interviews will compile information on real-world problems, mitigation measures, and research and development needs. As with the case studies, summary reports will be reviewed and approved by interviewees before the collected material is used to supplement the results from the case studies.

PROBLEMS ENCOUNTERED

One major difficulty with the case studies has been the identification of an adequate number of SI's suitable for the case studies. As noted, many of the sites had to be eliminated from further consideration, because of one or more of the following reasons:

- Absence of rigorous data and documentation on the original design and construction and on any subsequent problems and solutions.
- Lack of adequate monitoring data for meaningful performance assessment.
- Many potential sources of pollution at or adjacent to a site (e.g., landfills, waste piles, other SI's, etc.) that make it difficult to attribute any observed incident of contamination to a specific source.

RESULTS

Detailed evaluation of the data compiled for the six cases studied has resulted in the following assessments.

CASE STUDY NO. 1

The two FML-lined hazardous waste SI's at this site were designed and constructed by the owner in 1972 and 1979. Since no regulatory requirements governed the design and construction of such facilities at the time, no geotechnical and hydrogeological studies, environmental impact analysis, or laboratory or field investigations preceded the actual design and construction to develop sound basis for siting, liner material selection, foundation preparation, liner installation, QA/QC inspection, etc. Onsite availability of land was the primary consideration for SI site selection. Apparently, there was no rigorous QA/QC program or inspection of the completed SI's by professionals trained in FML design and installation.

Because of shortcomings, the SI's at this site have failed to provide satisfactory service. Limited water quality data from monitoring and production wells indicate contamination of both the upper and the lower groundwater aquifers, as evidenced by increases in the total dissolved solids, sulfate, and nitrate concentrations. Because cracks appeared along the exposed sides of the liner in one of the ponds, the liner in this pond was replaced once. Possibly, the liners in both ponds are now leaking. Because of the relatively high permeability of the geological strata underlying the plant (0.44×10^{-2} to 1.4×10^{-2} cm/sec) and the strong acidic nature of the heavy metal-bearing waste disposed to the SI's, any liner failure could result in a substantial underground waste release and hence presents major potential for groundwater contamination.

CASE STUDY NO. 2

The very satisfactory operation at this site indicates that (given proper site and wastewater characteristics) designing and constructing small ponds to provide satisfactory performance can be simple tasks.

Two very small (48 x 28 x 5 ft. and 30 x 20 x 3 ft.), relatively new, onsite impoundments serve this pesticide formulation and packaging plant which generates intermittent discharges of wash-down and rinse wastewater. The waste volume is very small, seldom exceeding 400 gallons per discharge, two to three times per month. Groundwater in the area is at 215 ft. The wash-down pond is lined with two layers of polyvinyl chloride (PVC) sheeting as the primary liner on both the bottom and the side slopes, and a 30-mil PVC as the secondary liner on the bottom only. The primary and secondary liners are separated by 1 ft. of gravel. The rinse-water pond is lined with 20-mil chlorinated polyethylene (CPE) underlain with 1 ft. of sand and a 10-mil PVC liner, with both liners extending along the bottom and the side slopes. The leak detection system for each pond is merely a single, perforated PVC pipe (a 3-inch pipe for the wash-down pond and a 1-inch pipe for the rinse-water ponds) extending halfway across the pond bottom and connecting to an observation well. A 1/4-in. fiberglass cover was recently placed over the primary liner in each pond for better protection against liner deterioration and damage during pond cleaning. A 20,000-gallon storage/equalization tank was also recently installed to control liquid level in the wash-down tank.

During the 4-year operation of the wash-down pond, no liquid was observed in the observation well. Since the rinse-water pond was placed in operation only in late 1982, similar results from the leak detection have not yet been reported.

CASE STUDY NO. 3

This facility, which has impoundments located in two separate areas, is an example of the differences in performance between poorly planned and designed ponds and well-planned ponds. Problems resulting from poor planning cannot always be fully and permanently corrected through piecemeal remedies applied as the problems surface. This fact is illustrated at Site A, where nothing indicates that detailed site selection investigations or pond design took place. When the facility was investigated in 1971, wastes were seeping through pond levees that had been built on top of old waste fill. Work was performed to correct the problem at that time, but seepage was reported again during investigations in 1978. At this time, specific levee permeability and thickness requirements were imposed, and the levees were rebuilt to conform to these requirements (5 ft. of clay with 10^{-8} cm/sec permeability or the equivalent). But leachate was discovered again in 1980, indicating that even the improved dikes were not able to prevent seepage.

In contrast to Site A, Site B was developed in 1971 with some effort to design ponds that would prevent waste migration. A site investigation was performed, and soil compaction and other design criteria were specified before construction. When the site was investigated in 1978, no seepage was reported, even though the levees did not all conform to the new permeability requirements and had to be modified.

Site A may not have been explicitly sited and designed to prevent waste seepage, though Site B was. This possibility appears to have been a significant factor in the performance of the facility with respect to seepage. Building Site A pond levees on a garbage foundation undoubtedly contributed to the seepage problem, and the displacement fill method of improving the dikes apparently was unable to solve the problem. Trench key work apparently did not provide a complete solution either, unless the leachate originated (as the facility owners contended) from an adjacent commercial landfill.

CASE STUDY NO. 4

The operating experience at this site illustrates (1) how the materials contained in the waste can provide an adequate barrier against further waste seepage under certain circumstances, and (2) how liner failure and poor performance can result from deviations from desired liner specifications, reliance on liner-waste compatibility tests that poorly simulate actual field conditions, inadequate attention to geotechnical factors, and poor design and operating practices.

The major surface impoundment systems at this fertilizer manufacturing facility are 14-acre "gypsum" ponds, an 8-acre evaporation pond, and a 38-acre cooling pond. The gypsum ponds are unlined sedimentation ponds that have been used to recover gypsum for almost 20 years. The natural build up and solidification of gypsum in those ponds have rendered them impervious. This fact has been verified by actual examination and permeability testing of the core specimens from the bottom, which have indicated the presence of a very hard, low-permeability material.

The FML-lined evaporation and cooling ponds have failed in the past and are currently leaking. The liner specifications, which were written by the facility owner, called for a material that would not deteriorate when exposed to a waste with the following characteristics: pH of 2, maximum temperature of 110°F, 0.5% sulfuric acid, 1.63% phosphoric acid, 0.05% chlorides, 0.5% fluorides, and 1.0% organics. Though the available data indicate that the liner met the alkali and acid (pH 3.0) resistance tests, the material may not have been tested with a waste simulating the above characteristics. The actual liner manufacturer warranty also provides for an acid resistance of 1% weight change versus an original specification of 0.3% (both at pH 3.0) and limits the definition of organics to only five specific compounds, the total concentration of which is not to exceed 1%. Geotechnical and soil investigations had indicated that the native clay had a high content of calcium carbonate. This soil characteristic (which would lead to gas formation underneath the liner in the event of acidic waste leakage through the liner) was also not addressed in the site and liner design.

Liner bubbles have been observed in the FML-lined ponds. Inspections during repairs suggested seaming failure as the main initial cause of the liner leak. Seepage of the acidic waste into the underlying carbonate-bearing clay resulted in the production of large volumes of gas. Since no provisions had been made for venting, gas accumulation helped spread the seams and further aggravated the leaking. An overhead discharge pipe that diverted wastewater from the gypsum ponds to the evaporation pond was also an apparent contributor to the seam failure problem in the splash area. This problem was eliminated by installing a splash pad after the liner area was repaired.

CASE STUDY NO. 5

This facility containing eight clay-lined impoundments demonstrates what can be achieved when the impoundments are well designed, constructed, and operated. The major reasons for the highly successful performance of these clay-lined ponds include: (1) the use of a very impermeable clay (which was available onsite) as liner material, (2) the use of competent design, construction, and inspection contractors, (3) a conscientious owner/

operator that closely scrutinized all phases of impoundment design, construction, and operation (from site selection to QA inspection), (4) extensive waste-liner permeability studies, (5) excellent QA/QC and recordkeeping during all phases of the project, and (6) good communication (input and feedback) between two different state regulatory agencies and all parties involved in the establishment of the ponds.

The performance of the impoundments is documented by many years of inspection reports and observation of the leak detection systems located beneath each pond. These leak detection systems were field-tested by state inspectors during construction. The good performance of the impoundment is not surprising, since the clay used to line these ponds has held the borate deposits mined at this facility for centuries.

CASE STUDY NO. 6

The operating experience at this site illustrates how poor impoundment design and inadequate construction, inspection and record keeping can lead to leakage and poor performance. Wastewaters began seeping laterally out of one impoundment because (1) sand lenses within the natural clay were not identified and removed as specified in the design, and (2) at least one of the embankments was not adequately keyed into unweathered clay to prevent lateral waste migration.

This commercial hazardous waste disposal facility contains three 5-acre SI's lined with in-situ clay (on the bottom) and recompacted clay embankments. Pond 8 receives geothermal and petroleum industry sludges and wastewaters, and the other two ponds are currently used for land treatment of organic sludges.

A soils investigation conducted before impoundment design indicated the presence of sand and silt lenses within the natural clay beneath the site. The design specifications called for (1) at least 2 ft. of natural clay (with a permeability of 10^{-8} cm/sec) beneath the ponds in which no sand or silt lenses were discovered during pond excavation and construction and (2) subsequent placement of recompacted clay. The wastes began to migrate laterally along a sand lens underneath the embankment and surfaced outside the impoundment because: (1) all sand and silt lenses were not detected by boring tests or during excavation and construction, and (2) at least one embankment of Pond 8 was not keyed into the natural unweathered clay as specified (and this noncompliance with specifications was apparently not discovered and documented during QC inspection).

Though no seepage has been detected outside the other ponds, the other embankments at the site may not have been keyed into unweathered clay. The inspection and engineering certification reports for the site are very poor and unclear on this point.

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TECHNICAL CONSIDERATIONS IN LOCATING SURFACE IMPOUNDMENTS AND LANDFILLS IN LOW PERMEABILITY SOILS

Dr. C. Clark Allen and Dr. Ashok S. Damle
Research Triangle Institute
Research Triangle Park, North Carolina 27709

ABSTRACT

The question of the anticipated life of waste disposal facilities located in either saturated or unsaturated porous media of low hydraulic conductivity needs further consideration due to the reduced pore velocities through such materials and the increased travel time this implies.

Technical issues have been identified which influence the degree of protection provided in saturated versus unsaturated soils with low hydraulic conductivity. Permit applications for landfills located wholly or partially in the saturated zone of soil require demonstration of effective containment on a case-by-case basis. A better understanding is needed of leachate movement in saturated soils with low hydraulic conductivity to accurately assess the potential environmental endangerment from the operation of landfills under these conditions.

Previous advantages which have been identified for locating surface impoundments and landfills in low permeability soils include pollutant adsorption/attenuation capability and containment of contaminants in the event of liner failure. Many naturally occurring low permeability clay soils are located with a water table near the surface of the clay. In addition, surface streams are often nearby. These clay soils often have heterogeneous and anisotropic hydraulic conductivities which permit surface seepage of contaminants.

The environmental implications associated with surface impoundments or landfills located in saturated soils with low hydraulic conductivity were identified and examined. A more detailed assessment of the potential environmental implications of landfill management was obtained than had been provided by previous studies, particularly the impact that heterogeneous and anisotropic saturated low permeability soils will have in influencing the movement of subsurface leachate releases. In addition, the influence of soil saturation due to capillarity above the water table on leachate movement was examined.

A number of numerical models are available to describe the groundwater flow with solute transport. Analytical solutions are also available for a limited number of situations and usually involve simplifying assumptions such as isotropy and homogeneity of soils. Numerical models generally employ either finite difference or finite element techniques to solve the governing flow and transport equations. Finite element schemes offer more flexibility over finite difference schemes but are also highly involved comutationally. In order to fully assess the environmental impact of landfills located in saturated soils with low hydraulic conductivity, the predictive models should incorporate the effects of soil heterogeneity and anisotropy and should be able to handle low hydraulic conductivities. With these considerations, the applicability of existing groundwater flow and solute transport models to the present case was investigated. Models typical of different numerical and analytical methods were compared for accuracy, cost, time requirement, and ease of use for a typical set of input parameters.

FIELD VERIFICATION OF AIR EMISSION MODELS FOR HAZARDOUS WASTE DISPOSAL FACILITIES

W. D. Balfour, C. E. Schmidt, R. G. Wetherold,
D. L. Lewis, J. I. Steinmetz, and R. C. Hanisch
Radian Corporation
Austin, Texas 78766

ABSTRACT

Field tests were conducted at four hazardous waste treatment, storage, and disposal facilities (TSDFs) in order to 1) measure volatile organic compound air emission rates and 2) collect the necessary data to estimate the air emission rates using available predictive models. The activities for which air emission rates were measured included various surface impoundments, active and inactive landfills, a landfarm, drum storage, and a solvent recovery operation. Due to the limitations of the existing air emission models, calculation of predicted emissions were limited to the surface impoundments and landfarm.

A direct comparison of emission rates measured using the concentration-profile technique and the emission isolation flux chamber was made based upon measurements at a surface impoundment. For most compounds, the flux chamber technique resulted in a statistically significant greater air emission rate than as measured by the concentration-profile technique.

The Thibodeaux, Parker, and Heck air emission model was used to predict emissions from three surface impoundments. Predicted emissions were compared to emission rates for ponds 1 and 2 measured using the flux chamber. No statistically significant differences were determined between predicted and measured emission rates in half of the cases examined for pond 1. In all other cases, the predicted rate was greater than the measured rate for pond 1. For pond 2, the predicted rate was orders of magnitude greater than the measured rate in all cases. This discrepancy is attributed to problems in modeling the sludge/oil/aqueous surface encountered for this lagoon. Predicted emissions were compared to emission rates for pond 3 measured using both concentration-profile and flux chamber techniques. In general, the predicted rates are statistically greater than those measured by the concentration-profile technique and less than those measured by the flux chamber. A predictive model was not used to estimate emissions from the inactive chemical landfills in light of the heterogeneous nature of the waste and inability of the model to account for vented emissions.

SOLIDIFICATION/STABILIZATION ALTERNATIVES FOR REMEDIAL ACTION AT UNCONTROLLED HAZARDOUS WASTE SITES

Murdock John Cullinane, Jr.
USAE Waterways Experiment Station
Vicksburg, MS 39180

ABSTRACT

Typically, the solidification/stabilization process involves the addition of solid and/or liquid reagents to produce a solid matrix with handling properties similar to soil matrices.

Planning for the application of solidification/stabilization technology to a particular remedial action site is divided into two distinct phases: process selection and scenario selection. The process selection phase is primarily concerned with the chemistry of the solidification/stabilization process as applied to the specific waste type; whereas scenario selection is primarily concerned with the development of equipment requirements, construction sequencing and cost estimating for accomplishing the selected solidification/stabilization process. The selection of an appropriate scenario must consider: safety and environmental concerns, available equipment, purchase and handling of solidification/stabilization chemicals, and handling of waste materials.

A review of current field practices indicates that four basic field scenarios have been successfully applied to the solidification/stabilization of waste liquids and sludges. These scenarios include in-drum mixing, in situ mixing, plant mixing, and area mixing. Various modifications to each of the above basic scenarios have also been developed.

Each scenario is documented and information is presented on equipment requirements, operating characteristics and capacities. A methodology for estimating the unit cost associated with implementing each scenario is also developed. A flow chart for selecting and implementing an appropriate process and scenario is developed and illustrated.

The development and selection of the solidification/stabilization operations plan for a particular remedial action site is dependent on several factors such as the nature of the waste material, the quantity of the waste materials to be treated, the location of the site, the physical characteristics of the site, and the solidification/stabilization process to be utilized. As a result, no conclusions are drawn as to the selection of a particular scenario for a specific remedial action project; however, the attributes of each scenario are developed and presented.

PREPARE TECHNICAL RESOURCE DOCUMENT ON DESIGN, CONSTRUCTION, MAINTENANCE, AND EVALUATION OF CLAY LINERS FOR HAZARDOUS WASTE FACILITIES

Leonard J. Goldman, Garrie L. Kingsbury, C. Clark Allen, Robert S. Truesdale,
Coleen M. Northeim, Scott M. Harkins, Ashok S. Damle,

Research Triangle Institute
P.O. Box 12194
Research Triangle Park, North Carolina 27709

and Mike H. Roulier

U.S. Environmental Protection Agency
26 W. St. Clair Street
Mail Stop 472
Cincinnait, OH 45268

ABSTRACT

The purpose of this project is to develop a Technical Resource Document (TRD) on clay liners for landfills, surface impoundments, and waste piles. The TRD will be a summary of the current technologies and evaluation techniques applicable to these facilities. Critical factors in the design, construction, and maintenance of compacted clay liners will be investigated and addressed.

Major research and development projects related to clay liner performance will be identified and their results compiled on an ongoing basis. Relevant information that is obtained through this data-gathering effort will be presented in the final TRD.

Another aspect of this project will be the presentation of the state-of-the-art knowledge and techniques currently used for clay liner design and installation. The project team will contact selected engineering firms, waste management companies, and professional associations to collect information on current practices for designing, installing, testing, and maintaining clay liners. Problems encountered during installation will be highlighted.

A data base documenting the performance of installed clay liner systems will be developed. Relevant information will be obtained from both governmental and private sources.

The influence of waste liquid composition on infiltration rate into partially saturated clay liners will also be studied. This analysis will, in part, be based on results of laboratory tests performed with various clay and liquid waste systems. In a closely related area, an effort will be made to document the accuracy achievable and the effort required to use available methods for predicting transit time of leachate in partially saturated compacted clay liners.

Research reports and the TRD Draft for public comment are scheduled to be completed in May 1985.

APPLICATIONS OF ENGINEERING FABRICS AT LAND WASTE DISPOSAL SITES

Raymond C. Horz
U. S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi 39180

ABSTRACT

Engineering fabrics have proven to be cost effective materials for solving numerous drainage and stability problems in geotechnical engineering, and they can potentially be utilized to solve similar problems in the containment and disposal of solid and hazardous waste. A variety of applications of engineering fabrics is presented which utilizes the filtration, drainage, separation, and reinforcement capabilities of these materials. The applications addressed include (1) construction of leachate collection and groundwater control systems, (2) protection of waste covers from surface erosion, (3) drainage blankets in landfill covers and waste disposal lagoons, (4) gas venting and puncture protection beneath synthetic membranes, (5) permanent capping of soft waste sediments, and (6) construction of haul roads and temporary working platforms on soft sediments. In each of these applications, design considerations and techniques, fabric requirements, and construction techniques are discussed. Model specifications for fabrics in the various applications are given. For drainage systems and erosion control, criteria for the selection of fabrics based on the fabric's piping resistance and clogging resistance are presented. Strength requirements based on the severity of the construction environment and long-term chemical/biological degradation are addressed. Fabric selection criteria are given for fabrics used for haul roads, for reinforcing dikes, and as a component of caps for soft sediments. Construction techniques are described for each of these applications.

Important physical, hydraulic, and endurance properties of fabrics are discussed. Tensile strength, modulus, and puncture resistance, as measured by the grab tensile test, the wide width tensile test, and the Corps of Engineers puncture resistance test, are emphasized as being the most practically applicable physical properties. Other physical properties such as creep susceptibility, tear resistance, frictional and pull-out resistance with soil, and seam strength are also discussed.

LEACHATE PLUME MANAGEMENT

Charles Kufs, and Edward Repa
JRB Associates
McLean, VA 22102

To successfully control leachate plumes from uncontrolled hazardous waste sites, a thorough understanding of plume dynamics and aquifer restoration technologies is essential. To address this need, a handbook has been developed which provides an overview of the fundamental concepts, procedures, and technologies used in leachate plume management. The handbook consists of eight chapters:

- Chapter 1 -- Introduction: Overview of plume generation and summary of the handbook's contents.
- Chapter 2 -- Plume Dynamics: Effects of groundwater flow patterns, leachate characteristics, and plume/geologic media interactions.
- Chapter 3 -- Plume Delineation: Data sources and procedures for estimating plume boundaries, characterizing plume chemistry, and extrapolating future plume movement
- Chapter 4 -- Control Technology Selection: Overview of plume control technologies and evaluation and selection criteria for site applications.
- Chapter 5 -- Groundwater Pumping: Well hydraulics, design, installation, operation, and maintenance.
- Chapter 6 -- Subsurface Drains: Drain hydraulics, design, installation, and maintenance.
- Chapter 7 -- Low Permeability Barriers: Barrier materials, placement, design, installation, and maintenance.
- Chapter 8 -- Innovative Technologies: Bioreclamation and in situ chemical treatment technologies.

Groundwater pumping technologies involve the extraction or injection of water, through wells, to alter a plume's movement. Extraction wells create a cone of depression causing groundwater to flow toward the well. A cone of impression is created around an injection well causing groundwater to flow away from the well. Groundwater injection and extractions wells can be used separately, or in combination, to change the flow of groundwater in order to contain a plume.

Subsurface drains are continuous, permeable barriers designed to intercept groundwater flow. They can be used much like wells, especially in low permeability aquifers. Groundwater collected in drains or wells generally must be pumped to a treatment system. This additional water can increase the treatment facilities operation costs substantially.

Low permeability barriers consist of a wall or other appropriate configuration of low-permeability material constructed underground for the purpose of isolating contaminants or diverting groundwater flow. Slurry trench barriers are used to contain contaminant plumes by completely surrounding a waste site, capture insoluble contaminants migrating down gradient, or lower a groundwater table to prevent contact with wastes. Grout barriers can be constructed similarly to slurry trenches but high costs and technical difficulties generally restricts the use of grouts to sealing fractures and other large openings in aquifers.

In addition to these more established techniques, innovative technologies are being developed to control leachate plume movement. These include in situ biological and chemical treatments.

TECHNICAL HANDBOOK FOR DESIGN AND CONSTRUCTION OF COVERS FOR UNCONTROLLED HAZARDOUS WASTE SITES

Colin C. McAneny
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi 39180

ABSTRACT

This technical handbook provides guidance to the cover-system designer and technical information for regulatory personnel. A properly designed and maintained cover system reduces percolation and leachate formation, prevents contaminated dust emissions and contaminated surface runoff, and results in rapid aesthetic improvement to a site.

Most materials used in any cover system are likely to be soils, which are best classified by the Unified Soil Classification System (USCS). Soils may be stabilized or modified by the use of soil additives such as lime, bentonite, portland cement, fly ash, or bituminous materials. Other applicable materials in a cover system may include impermeable substances such as asphalt and synthetic "geomembranes," and permeable substances such as various waste or residual materials, pipes and tiles, and synthetic "geotextiles." Significant properties of all these materials are discussed in the handbook, and tests and criteria for them are described or referenced.

Proper cover-system design requires decisions regarding design life of the system, tolerable quantities of leachate, and future use of the site. To estimate the amount of leachate expected from a given design, it is necessary to perform a water-balance analysis.

To provide for various functions and attributes, the most efficient cover system is one composed of layers. From bottom to top, the layers in a cover system may be as follows: a gas-permeable layer to control gases produced by organic decay within the wastes; one or more filter layers where materials of contrasting gradation are placed in direct contact with one another; a foundation or buffer layer to serve as a platform on which to build the rest of the system; a hydraulic-barrier layer, composed of either impervious natural soils, amended soils, or a geomembrane; a drainage layer, to intercept percolating water and provide a path for it to a disposal outlet; a biotic barrier layer to stop animals and plant roots from penetrating and disrupting the hydraulic barrier; and a surface layer to provide for vegetative support, stabilize the surface against erosion, aid in dewatering the cover through evapotranspiration, and provide an aesthetically pleasing appearance. An effective surface water management plan is essential to control surface runoff.

Good construction is as important as good design. The handbook discusses methods and equipment used in cover construction, and organization and practices important for construction quality control.

Two case histories of existing cover installations at hazardous waste sites are presented to demonstrate some of the cover design concepts described in the handbook.

TESTING AND EVALUATION OF PERMEABLE MATERIALS FOR THE REMOVAL OF POLLUTANTS FROM LEACHATES AT REMEDIAL ACTION SITES - BENCH AND LABORATORY TESTING

James E. Park
University of Cincinnati, T&E Facility
Cincinnati, OH 45268

ABSTRACT

Conventional practices for controlling pollutant migration at remedial action sites seek to restrict ground water flow. Impermeable barriers such as slurry walls and grout curtains, ground water pumping wells and/or surface drains can restrict contaminant movement. These pollutant migration management techniques, however, do not mitigate their toxicity.

"Permeable barriers," using materials that can reduce the concentration of contaminants in solution by sorption, precipitation or other mechanisms may be a viable addition to the alternatives available for remediating a hazardous waste site. Permeable materials would allow the ground water flow to be maintained while the pollutant load is decreased.

There are many materials that might be used for this purpose. Activated Carbon and man-made zeolites have been extensively tested in pollution control and industrial treatment operations. These materials, along with many synthetic, commercial sorbents would seem appropriate, however the quantities required at most sites, may make them cost prohibitive.

Natural materials such as limestone, coal and clay, and waste products such as fly ash may offer some capability in removing contaminants from leachates. They also are comparatively low in cost and are generally available throughout the country. It is unlikely that any one of the four materials mentioned above has the ability to retain all of the possible contaminants that may be encountered at a remedial action site. This project will examine multiple layers of available, inexpensive materials to evaluate the effectiveness of various layer orderings, appropriate layer thicknesses and the individual materials' abilities to retain a leachate's contaminants.

If the results are sufficiently positive, they will be used to develop a protocol for testing these and other suitable materials with actual leachates. The intention of such a protocol will be to provide site-specific data and design information for the use of a "permeable" barrier at a remedial action site.

The Technical Project Monitor for this work is Mr. Jonathan G. Herrmann, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Solid and Hazardous Waste Research Division, Cincinnati, Ohio.

IN SITU TREATMENT TECHNIQUES APPLICABLE TO LARGE QUANTITIES OF HAZARDOUS WASTE CONTAMINATED SOILS

Ronald C. Sims
Utah Water Resource Laboratory
Utah State University, Logan, Utah

Kathleen Wagner
JRB Associates
McLean, VA

ABSTRACT

In situ treatment may be a practical and economical approach to the treatment of large volumes of hazardous waste contaminated soil. A literature study and evaluation was conducted to determine in situ treatment techniques which may be used as alternatives to excavation, hauling, and disposal of contaminated soil. Specific site scenarios addressed for in situ treatment included low level contamination around the periphery of a site, in the hot or contaminated zone after the bulk of contaminant removal, or across a broad terrestrial system.

Three alternative treatment schemes were considered for in situ treatment. These include: 1) management of the soil system to utilize natural soil reactions for treatment (degradation, detoxification, or immobilization of waste constituents); 2) addition of treatment agents to the soil; and 3) washing or flushing the soil to remove contaminants. Treatment techniques evaluated and selected for the first two schemes involve sorption processes to control mobilization; biological processes to control degradation and detoxification; and chemical and photochemical processes to control detoxification, degradation, and immobilization. Soil flushing, involving the elutriation of contaminants from soil, followed by treatment of the elutriate may also be used.

A total of forty in situ treatment techniques were identified. Fourteen techniques for treatment of hazardous inorganic constituents were evaluated including precipitation, organic matter addition, chelation, reduction and oxidation, sorption by soil, activated carbon, zeolites and soil flushing. Twenty five techniques for treatment of hazardous organic constituents were evaluated including: 1) immobilization through soil moisture control, soil incorporation, and sorbent addition; 2) chemical treatment through soil catalyzed reactions, addition of oxidizing and reducing agents, and soil pH adjustment; 3) biological treatment including, management of aerobic and anaerobic environments, analog enrichment, and addition of exogenous acclimated or mutant microorganisms and cell-free enzymes; 4) soil flushing; and 5) control of volatilization through physical and chemical barriers.

A methodology was developed for selection and implementation of in situ treatment methods based on: 1) characterization of the site, soil, and waste; 2) assessment of the environmental impact of the waste; 3) treatment technique selection; and 4) monitoring to evaluate treatment success.

Results of the evaluation of in situ treatment techniques that have been used to treat hazardous waste contaminated soil indicate that, although several techniques appear promising, very few have been field tested. It is therefore necessary to conduct bench and site specific pilot scale testing of potential treatment techniques to determine the extent of applicability at CERCLA sites.

CONTAMINANT FIXATION: PRACTICE AND THEORY

H. R. Lubowitz, R. W. Telles, B. M. Eliash, S. L. Unger
Environmental Protection Polymers, Inc.
Hawthorne, California 90250

ABSTRACT

Data from a literature review are used to describe and evaluate elements of hazardous waste fixation. Factors are then identified for producing high-performance stabilized hazardous wastes, and some conclusions are drawn about the performance of current stabilization techniques. Some suggestions are made for future research.

INTRODUCTION

Though the current trend in managing hazardous waste is either to destroy or reuse toxic residue,(1) the formation of some unmanageable waste is usually unavoidable.(5) Such materials are generally disposed of on the land by broadcasting them in small concentrations or by fixing them in large concentrations within a binder that prevents or restricts contaminant release into the environment. U.S. Environmental Protection Agency (EPA) toxicity tests have shown that fixation processes in current use may not, in fact, achieve the high performance levels claimed for them.(7) In addition, future fixation products will be even more difficult to manage with binders as fixatives because improved waste treatment processes will yield wastes with higher concentrations of contaminants. The purpose of this paper is therefore to examine contaminant fixation practices and establish criteria for producing high-performance fixation products. Examination of these criteria and an understanding of their scientific principles can provide a basis for predicting performance of stabilization processes and products.

ELEMENTS OF HAZARDOUS WASTE FIXATION

There are several factors to consider in judging the expected cost and performance or merit of a contaminant fixation process using binders. These include (1) the waste to be fixed, (2) the binder (fixative) used, (3) the type of product formed (solid solution, chemically fixed product, or microencapsulate), (4) processing techniques, and (5) stability of the product under expected environmental stress. The most important factors in judging performance are items 3 and 5, the type of product formed and its stability. By carefully examining these two factors, one can judge the relative merits of any proposed fixation process for managing any type of waste. Information about each of these was gathered in a literature review and is discussed here briefly.

Wastes to be Fixed

The compositions of waste materials are highly variable and often defy tight definition. Wastes of concern, however, are primarily hazardous industrial wastes. Those most amenable to contaminant fixation by current stabilization processes used are normally produced in large amounts. They consist mainly of inorganic materials in aqueous solution or suspension and contain large amounts of heavy metals or inorganic salts. Organic wastes and waste streams containing organic constituents are less amenable to contaminant fixation by state-of-the-art processes.

Binders Used

A great variety of binders are used for hazardous waste stabilization, including naturally-occurring clays, lime-based cements, scrap plastics, and fly ash. Such materials are economical, but their performance properties under waste disposal conditions may be highly variable. These uncertainties along with those of the highly variable waste feeds produce fixation products whose performances may not be predictable in the field. A key factor in determining product performance is the stability of the binder. Even though the stability of the binder alone is less than optimal, it may still be acceptable depending on the type of product it forms when combined with waste.

Binders (fixatives) are of two types--organic and inorganic. They may be classified as follows:

1. Organic fixatives:
   - Asphaltic and bitumens
   - Ureas and phenolics
   - Epoxides and polyesters
   - Vinyls
2. Inorganic fixatives:
   - Cements and concretes
   - Calcium compositions
   - Silicates
   - Sulfur compositions

Inorganic cements are the most commonly used fixatives and are employed mainly for fixing heavy metal contaminants eventhough organic fixatives are generally more chemically stable than inorganic ones. They are also more physically stable, but as nonreinforced materials their load bearing properties may not be comparable. Raw material cost considerations and familiarity presently favor the use of inorganic fixatives.

Types of Products Formed by Fixation

Because waste and binder compositions vary considerably, it is difficult to use these factors to predict expected performance of the products in the field. A better approach is to examine carefully the types of end products formed with hazardous waste fixation processes--solid solutions, chemically fixed products, and microencapsulates. These products and their merits with regard to contaminant fixation are defined briefly as follows:

1. Solid solutions consist of submicroscopic contaminant particles (most likely in the molecular and colloidal size range) dissolved in a solidified fixative and characterized by weak chemical interactions such as Van der Waals forces. Solid solutions should generally be avoided because the weak chemical bonds could permit contaminant loss through diffusion. They may be acceptable in some cases, however, if the permeates and the fixative are such that they retard contaminant diffusion. For examples, solid solutions may contain high molecular weight contaminants and binders having macromolecular structures characterized by chain cross-links and entanglements.

2. Chemically fixed products consist of submicroscopic contaminant particles (most likely in the molecular and colloidal size range) incorporated in a fixative and characterized by strong chemical interactions with the fixative such as chemical bonds. Hazardous waste products that are truly chemically fixed are difficult to achieve but are highly desirable in all cases since contaminant molecules are expected to resist diffusion because of their strong chemical bonds to the fixative. Strong chemical bonds refer to bonds with high dissociation energies and indicate, but not invariably, high bond resistivities to chemical dissociation (e.g. hydrolysis). The great merit of chemical fixation is that the fixative can hold contaminants even though the fixation product may fragment under service conditions.

3. Microencapsulates consist of microscopic and macroscopic contaminant particles individually encased in a fixative that does not significantly affect the contaminant molecules because they are unavailable for interaction. Microencapsulation can yield high-performance contaminant fixation if the products maintain their integrity under environmental stress.

The merit of microencapsulates under service conditions can be estimated by monitoring their surface areas or (at least) of their dimensions. An ideal microencapsulate will exhibit no change in surface area, whereas that of a less acceptable microencapsulate will degrade and may provide a path for contaminant release.

Processing

Processing techniques for fixing hazardous wastes involve mixing in an attempt to homogeneously disperse the contaminants throughout the fixative. Thus the nature of the fixative largely determines the type of processing required for blending and isolating the product.

Inorganic fixatives are processed mainly at ambient temperatures and use water to effect their consolidation. In some cases, water is immobilized by the fixative without being chemically incorporated.

The processing of organic fixatives may require greater than ambient temperatures and may or may not require water. The presence or absence of water in processing is important to determining the performance levels of the final product, since water is the vehicle by which all contaminants but gaseous ones are released and dispersed in the environment. Without water contact, contaminants remain fixed.

Stability and Performance of Fixation Products in the Field

Fixation product performance is assessed by considering the following:

1. The size of the contaminant particles in the fixative (submicroscopic versus microscopic and macroscopic),
2. Orientation and strength of the interfacial forces acting on submicroscopic particles (nondirectional and weak, as in solid solutions, versus nondirectional/directional and strong, as in chemically fixed products), and
3. Accessibility of leachate to the contaminant particles (limited or constant surface area of the product versus increasing surface area and eventual fragmentation of the product under service conditions).

Contaminant Particle Size

The particle size of the contaminant and how it is dispersed in the fixative greatly affects the ability of a process to fix that contaminant. Submicroscopic particles are affected much more than microscopic or macroscopic particles by the chemical forces at the contaminant particle interfaces. For example, submicroscopic contaminants are released by leachate at the wetted surface of the fixed product. More contaminant particles then diffuse from the interior to the surface in response to the decreased concentration gradient leading to the surface. The diffusion is enhanced by high concentrations of submicroscopic particles.

Microscopic and macroscopic particles are also released by contact with eachate at the wetted surface of the product. But diffusion of these contaminants through the product is impeded because the particles are large and can be insoluble in the fixative. Thus, current fixation products seem functional, but eventually the fixative moiety itself breaks down, exposing more particles to leachate and accelerating the loss of contaminants.

Our work indicates that most fixatives in current use stabilize contaminants through microencapsulation rather than through chemical fixation or solid solution. Microencapsulation is the main vehicle for contaminant fixation even though chemical reactions may occur between contaminants and fixatives. A truly chemically fixed product is not likely to be produced in current practice because the required dissolution of the reaction products by the fixative is in reality not probable under the processing conditions generally employed. Instead, the processing produces microscopic and macroscopic particles that are entrapped (encapsulated) as the fixative solidifies. Such products should be considered microencapsulates.

Orientation and Strength of Interfacial Chemical Forces

Weak, nondirectional chemical interfacial forces characterize solid solutions, and strong directional or nondirectional forces characterize chemically fixed products. Thus the submicroscopic contaminants in solid solutions are much more readily released from the fixative to the leachate than are those in chemically fixed products. These forces affect the stability of microscopic and macroscopic contaminant particles only minimally. They are important, however, in estimating the mechanical performance of the products.

Accessibility of Water to Contaminant Particles

Accessibility of water to fixation products depends on the product's surface area and the extent to which that area is wetted. A preferred product is one that maintains a microscopic surface area that approximately equals the geometric area of the monolith, or at the very least, one that has a constant surface area or becomes constant before the mechanical properties of the product are significantly affected.

Thus the effectiveness of a preferred product depends on minimizing the surface area, which is the site for contaminant release and transfer to the environment. Some preferred products perform better than others. In a solid solution, for example, the contaminant is dissolved in the fixative and thus is available at all the wetted surfaces of the product. But in a preferred microencapsulate the contaminant is physically encased and not dissolved. Thus only those contaminants in particles actually at the surface are released. The contaminant in a preferred microencapsulate is not available at the surface except for a relatively few particles that remain exposed after processing. Further release of contaminants would not occur as long as the particles remained insoluble in the fixative and the product remains intact.

A nonpreferred product, on the other hand, shows continual increase in its surface area under service conditions and may finally disintegrate. Processes that yield nonpreferred products can be used for waste stabilization if contaminants are chemically fixed to the binder. In such cases, even though the surface area may not remain constant, the product can be useful because of the appreciable time needed for the monolith to disintegrate into water entrainable particles. But if the product is not a chemically fixed one, a nonpreferred product exposes contaminant particles to leaching in a relatively short time through the ready formation of flaws, cleavages, capillaries, etc. in the monolith.

The type of water action on the product is also important--static, flowing, etc. Static action can activate release of contaminants because of salting in effects, or it can retard it by common ion effects. Even under leachate flow, static water exists in flaws, cleavages, and capillaries. This static water can also induce chemical and physical changes in the product's surface, which may then perhaps transpire contaminants more readily than possible with contact by virgin leachate only.

PROBLEMS IDENTIFIED IN PRODUCING STABILIZED PRODUCTS

As mentioned, our observations indicate that state-of-the-art fixation products in current use are really microencapsulates. As such, contaminant release occurs mainly at the interface of microscopic and macroscopic particles with water (leachate). Water normally contacts the contaminant only at the product surface and in its flaws. However, enough water may be used in the process of consolidating some fixatives so that it characterizes the matrix as it does in a gel.(8, 13) This water may solubilize contaminants and thus promote contaminant diffusion and additional contaminant loss.

Solid solutions and chemical fixation products were not readily available for study because state-of-the-art fixation products generally hold microscopic and macroscopic insoluble heavy metal contaminants. Exceptions occurred only in high temperature sintered products. In the future, however, organic contaminants may be dissolved in organic fixatives to produce solid solutions. This procedure will not be easy to carry out. An appreciably more difficult task would be to attach the contaminant chemically to the fixative.

CRITERIA FOR PRODUCING HIGH-PERFORMANCE STABILIZED PRODUCTS

Based on our work and the literature review conducted for this study, we have established the following criteria for producing high-performance stabilized products:

1. Fixatives (binders) selected for use with hazardous wastes must be chemically and dimensionally stable under expected service conditions, both before and after the waste has been incorporated. For example, asphalt binders would not be expected to provide dimensional stability to a solidified waste even though such materials are chemically stable.

2. For a chemically fixed product, processing should disperse contaminants throughout the fixative in the molecular or colloidal state, and it should incorporate contaminants in that state by strong chemical forces within the matrix rather than by weak chemical bonding forces. That is, the contaminant must be chemically grafted to the molecular structure of the fixative.

3. For a microencapsulate, encasement of the microscopic and macroscopic contaminant particles by the fixative must be as complete as possible. Ideally, 100% of the particles would be completely encapsulated. Careful processing conditions are required to achieve this goal, however.

4. Stabilization of microencapsulates should be enhanced by minimizing the surface area of the product potentially exposed to leaching solutions.

5. Formation of leachate insoluble particles would enhance the stability of microencapsulates.

CONCLUSIONS

Our review of the literature indicates that the mechanism predominantly used for fixing contaminants in available processes is actually microencapsulation and not chemical fixation(6), as claimed by several manufacturers. Though some fixatives (e.g., silicates, lime, and cement) were believed to cause molecular dispersion of contaminants and to effect chemical fixation,(3, 4, 10, 12) our work indicates that only minimal amounts of contaminants are actually fixed in molecular or colloidal dispersion.

In fact, fixing agents react with heavy metal contaminants and cause precipitation of microscopic and macroscopic particles that are presumed to resist dissolution by water (leachate).(2) Waste is sometimes pretreated to condition contaminants to be reactive with the fixative.(9) When the product is consolidated, the particles are locked into the fixative (i.e., encapsulated). Thus even if the consolidated products are water permeable, the contaminants will not be released because they are in an insoluble state.

There are means other than precipitation to form water-insoluble compounds. Wastes can be treated with additives to produce contaminant particles that resist water action. The preferred approach is to cause chemisorption of contaminants onto leachate-stable particles.(11) This approach is, nevertheless, inferior to chemical fixation because the chemisorbed particles may be small enough to be subjected to water action.

We believe that fixation products holding heavy metals, in general, are acceptably stable only when contaminant particles are all completely encased in water-tight compartments (i.e., microencapsulated). The reason for this conclusion is that leachates specified in the regulatory guidelines for assaying contaminant stabilization dissolve the heavy metal oxides and silicates that are believed to resist dissolution. We found it nearly impossible in most cases to form heavy metal compounds that were stable when contacted with the specified leachates.

We are currently investigating means for stabilizing microencapsulated contaminants in organic binders so that total encasement of particles would be unnecessary and future processing demands would be less rigorous. One approach is to reduce the soluble ionic character of heavy metal compounds by introducing dissolution-resisting covalency into the composition. Thus, we view polysulfides and organo-sulfides as being more suitable than sulfides, oxides, and silicates in producing leachate-stable heavy metal contaminant particles.

Acknowledgements

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MULTIPLE SOIL LAYER
HAZARDOUS WASTE LANDFILL COVER:
DESIGN, CONSTRUCTION, INSTRUMENTATION, AND MONITORING

Richard C. Warner, James E. Wilson, Nathaniel Peters
Agricultural Engineering Department
Harry J. Sterling
Civil Engineering Department
University of Kentucky
Lexington, Kentucky
40546-0075

Walter E. Grube
Municipal Environmental Research Laboratory
United States Environmental Protection Agency
Cincinnati, Ohio
45268

ABSTRACT

The design, construction, instrumentation, and monitoring of three multiple soil layer landfill covers are described in detail. The major scope of this research is to ascertain the hydrologic balance of such a cover with emphasis placed on soil moisture movement throughout the layered soil profile. The experimental design allows for the evaluation of numerous alternative design options. These include alternative pervious drainage spacing and leachate collection systems. The construction phase of this project is presented in detail, encompassing a comprehensive analysis of the clay, sand, and topsoil layers, as well as drainage and subsidence provisions of the experiment. A multi-layer, multi-sensor soil moisture system employing tensiometers, resistance blocks, thermocouples, and the neutron probe is presented with emphasis placed on installation without disturbing the effects of construction equipment or the integrity of the multi-layered cover. A tipping bucket system was designed to measure surface and subsurface drainage to within ±0.5% of the actual discharge. Calibration of resistance blocks yields a log/linear relationship between resistance and soil moisture content. The multi-sensor approach provides a comprehensive data base for multi-layer cover modeling used to evaluate alternative designs.

INTRODUCTION

Project Scope

The overall scope of this project is to design, construct, instrument and monitor a multiple soil layered hazardous waste landfill cover. The objectives are twofold: (1) delineate the procedure used to construct a multi- layered cover that meets current regulatory requirements, and (2) ascertain the hydrologic balance of such a cover with emphasis placed on soil moisture movement throughout the layered soil profile. Phase II of this project includes a more extensive period of data gathering and model applications to extend results to evaluate alternative multi-layered cover operations/designs.

Site Description

Tyrone, Kentucky is the location of this project. The research site is located 22 miles southwest of the University of Kentucky at Lexington, Kentucky. Selection of the site was based upon: (1) a required natural land slope of less than four percent in order to minimize construction costs, (2) an acceptable source of clay and topsoil materials, and (3) convenient administrative and logistic aspects.

PURPOSE

Synopsis of Multi-Layered Design

The purpose of this section is to provide a capsule overview of the multi-layer landfill design and in-place instrumentation. A thorough discussion of design, construction, and instrumentation procedures is presented later.

Dimensions

Three multiple soil layered landfill covers were constructed in order to monitor the hydrologic balance of such a system. Each cell can be viewed as a slice from a large hazardous waste site. An overview schematic is shown in Figure 1 illustrating the major features of the cells. Each cell was constructed on a three percent grade, 27 m in length and 6 m wide. Overall cell height is 3 m. The layers from bottom upward are: (1) protective sand layer (0.3 m), (2) PVC 20 mil liner to prevent moisture movement in or out of cell, (3) sand to be augered out during the subsequent hydrologic effect of subsidence studies (0.9 m), (4) compacted clay liner (0.6 m), and (5) sand (0.6 m), and topsoil (0.6 m) (Figure 2)

Drainage

Perforated PVC pipe was installed at six locations in each cell. Lengthwise, drainage pipe was positioned 9, 18 and 27 m from the upslope point. Pipes were situated at the bottom sand/plastic liner interface and at the sand/clay interface (Figures 2 and 3). Placement at these positions enables determination of the influence of either 9 or 27 m spacing as well as leachate collection and/or reduction of head on the clay layer due to lateral removal of water along the top sand layer. Both of these techniques have been employed in proposed landfill cover designs. Also, surface drainage was provided by three half-round PVC pipes located at the 9, 18, and 27 m marks. All drains were placed on a one percent slope toward the observation pits.

Instrumentation

Flow from all twenty-seven drains is directed to tipping buckets installed in the observation pits. (Figure 3). The tipping buckets are used to measure flow from the drainage tiles. Since emphasis is being placed on the movement (both upward and downward) of soil moisture, several redundant instrumentation systems are used. Soil moisture is being determined via: (1) tensiometers, (2) gypsum (resistance) blocks, (3) thermocouple wire, and (4) the neutron probe. Six each of tensiometers, resistance blocks and thermocouples are installed near the center of the cell above and below all soil interfaces. Also, three access tubes are located as shown in Figures 2 and 3.

APPROACH

Construction

Site Requirements

The site for the multi-layered landfill project is at Tyrone , Kentucky. Prior to actual landfill construction a gravel road with appropriate subbase and drainage was built. Two hundred-twenty volt, single phase 200 amp service power was installed at the field fabrication building and adjacent research locations. A 1.6 m high tensil strength fence was provided under contract to exclude cattle. The field fabrication building was constructed to provide a work area to construct and assemble required materials and instrumentation for the landfill cells.

Preliminary Requirements

Excavation for the 3 m deep cells required the removal of topsoil and 2.3 m of limestone. The limestone was removed through use of a hoeram. This operation required five weeks of continuous hoeram usage and produced a rough grade of approximately three percent. The hoeram was also used to smooth the cell walls to prevent highly irregular surfaces. Approximately 10,000 polyethylene sandbags were filled and placed along cell walls to protect the liner from sharp rocks and provide the 27 m by 6 m cell dimension. Also, these sandbags were used to support the uppermost sections of the cells that were located slightly above the natural land grade.

Next, the placement of Fibretex fabric along the cell sides was installed to provide additional protection from puncturing the 20 mil PVC liner. Sand was placed

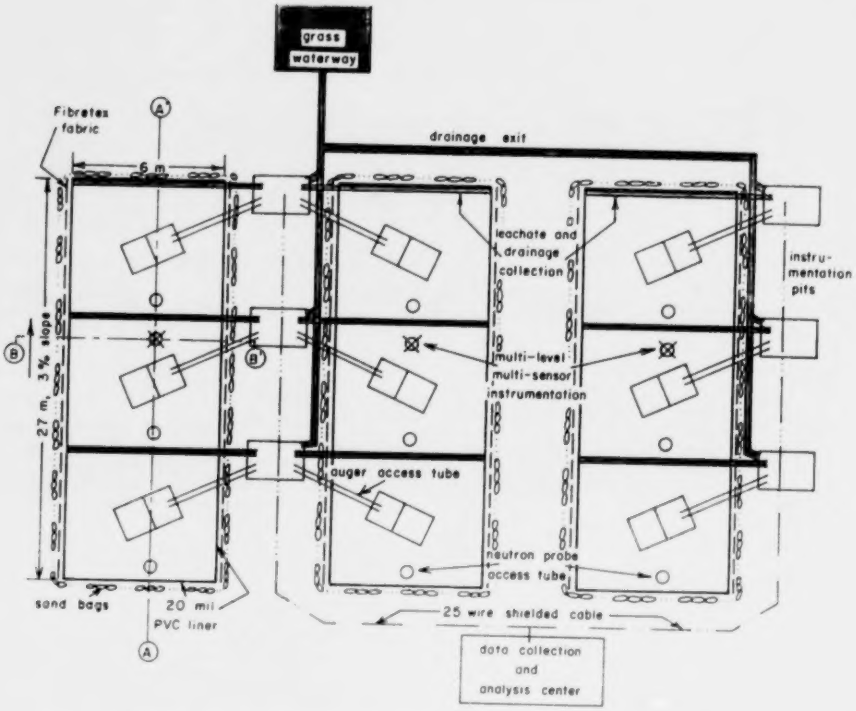

Figure 1. Plan view of multi-layered cover cells

to protect the bottom of the liner from rock fragments. Also, the sand afforded a uniform three percent slope along the cell base.

A single sheet of 20 mil PVC liner, 15.24 m by 30.48 m, was placed to completely encapsulate the sides, ends and bottom of the landfill cell. The liner was continuously checked to determine that its water-tight integrity remained intact. On the few occasions when small punctures or tears were discovered patches were immediately installed and visually inspected.

Subsidence Provisions

In order to provide the option of determining the hydrologic consequences of subsidence in a multi-layered cover access for an augering system was provided. Three 15.24 cm diameter PVC pipes, 4 m in length, were placed above sheets of marine plywood located on a 2 cm cover of sand above the plastic liner. Auger access pipes, shown in Figure 1, were placed to allow later insertion of a guide sleeve and auger device. This auger access system provides the opportunity to remove a known quantity of sand, thus developing a given void space at three desired locations along a cell. The created space could simulate any size void expected to occur in hazardous waste materials. Hence, studies of subsidence, clay layer fracturing, etc., could be conducted to measure associated water movement throughout the multi-layered landfill cover.

Leachate Collection

As stated in the synopsis section of this paper alternative leachate collection facilities were installed across the cell at a 9 m spacing along the length of the cell (Figure 1). Leachate collection was provided by PVC pipe which was drilled with 0.8 cm diameter holes spaced 2.5 cm apart. Approximately 120 holes were drilled per meter length, yielding the surface area typical of tile drainage. Fibretex fabric was wrapped around the drain pipe to prevent entrance of sand. The leachate collection pipes were placed on a one percent slope across the width of the cell. Compacted

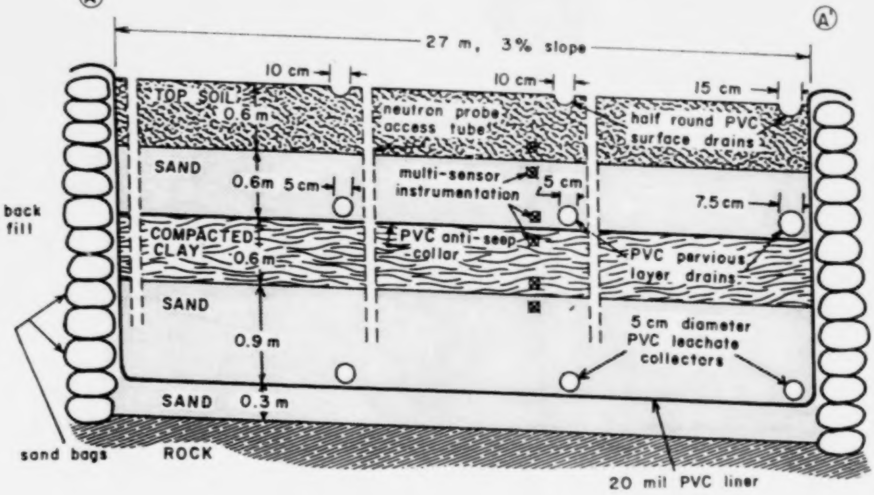

Figure 2. Cross section of multi-layer landfill cover (A - A')

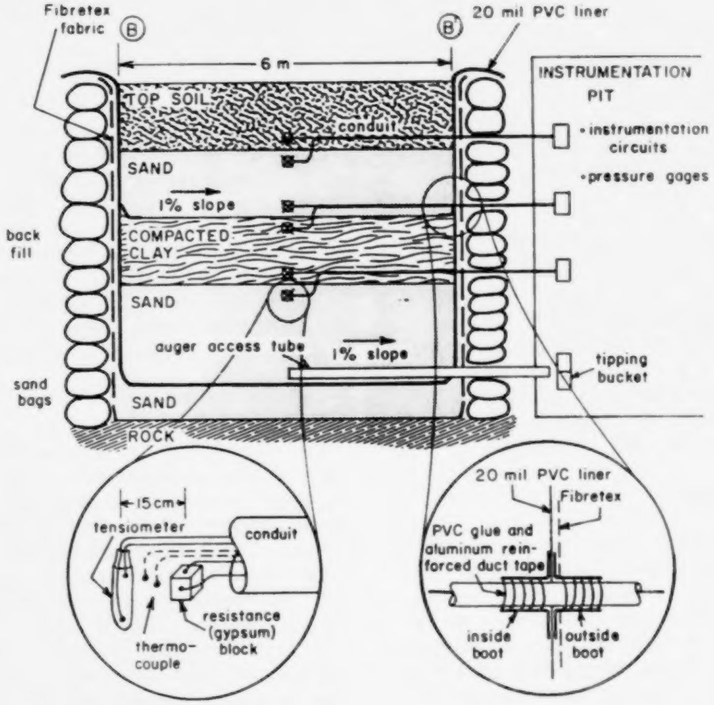

Figure 3. Cross section of multi-layer landfill cover (B - B')

clay and plastic were placed beneath the collector pipe to prevent any downslope flow under the pipe. The pipes located 9 m and 18 m along the 3% slope may be plugged by pipe inserts such that both 9 m and 27 m drain spacing can be evaluated. Flow exiting the leachate collection pipes is measured by automatic recording tipping buckets.

Simulated Waste Layer

Nine-tenths meter of sand was placed by a 0.44 m^3 bucket skid-loader. A total of 1,635 metric tons of sand was used for sand layers on all cells. Ninety tri-axial truck loads were delivered to the research site. The depth of sand was used to simulate hazardous waste such that the material could be augered for the subsidence study. The sand was covered with 10 cm of clay provided as an upper driving surface.

Instrumentation was located approximately 10 cm deep in the sand layer. Note that soil moisture instrumentation was placed above and below all soil layer interfaces at the time of construction in order to achieve a true measure of the influence of construction equipment upon soil moisture movement throughout the layered soil profile. Tensiometers, gypsum blocks, and thermocouple sensors were placed above and below each interface. Lines from all instruments were placed in conduit to prevent crimping from construction equipment loads.

Description of Compacted Clay Liner

An excellent clay source was located within 0.25 km of the cells. Extensive soil testing was conducted: (1) Procter density, (2) particle size analysis, (3) liquid limit, (4) plastic limit, (5) plasticity, (6) permeability, and (7) soil moisture-tension. Numerous trial tests were conducted using a wheel-roller, sheeps-foot and a Dynapac compactor to determine the ability to blend respective clay lifts and produce a relatively impervious clay liner. Documentation of soil moisture and density for each lift was determined by nuclear density, sand cone test, and gravimetric samples taken throughout each lift. Additionally, cores were removed from each cell for in-lab analysis of permeability and subsidence testing.

Description of Clay Layers for Cover

The two foot thick clay layers for the landfill covers for cells 1 and 2 were constructed using five lifts of a brown, silty clay. The clay used, from a local borrow pit, is a Type CH, based on the Unified Soil Classification System, with a plastic limit of 30, a liquid limit of 57, and a plasticity index of 27. It has a specific gravity of 2.76.

Construction initially involved placing the clay across the whole surface of the plot, tilling the soil to break up any large clods, removal of small rocks which were present in it, adding water when below the optimum moisture content, and then using a vibratory compactor to achieve the desired density.

Field tests were conducted to determine lift height and the number of compactor passes necessary to achieve 90% compaction. Initial soil moisture ranged from 22 to 27%. The maximum density from the standard Procter test was found to be 1525 kg/m^3 at an optimum moisture content of 25.7%. The average density from Cell 1 was 1458 kg/m^3 and for Cell 2 it was 1442 kg/m^3, and the average moisture content was 29% for Cell 1 and 28% for Cell 2 (Figure 4).

A soil moisture of approximately 28% was selected for actual compaction. This above optimal soil moisture represents a compromise between density and plasticity. A higher than optimum soil moisture allows for greater plasticity which may be needed for later cover subsidence. It was found to be difficult to incorporate the desired soil moisture throughout the lift profile.

Of special concern was the ability to blend or mesh lift layers together. It was found that no matter how many equipment passes were made, the two lifts oftentimes contained a slight separation. This problem was resolved by rototilling the following clay lift prior to compaction. The rototilling operation roughened the prior compacted layer and eliminated or greatly reduced the separation problem. Also, this procedure assisted in thoroughly incorporating soil moisture throughout the lift profile.

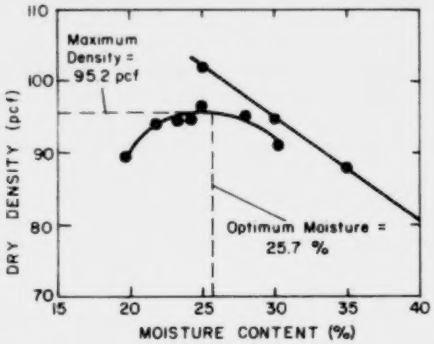

Figure 4. Procter Moisture Density Curve

Clay placement was accomplished by five lifts approximately 15 cm in height. A Dynapac CA12PD self-propelled, vibratory compactor, which has an operating weight of 3254 kg, was used for compaction. It has 72 drum pads, each with a contact area of 87.1 cm^2, arranged in a chevron pattern. The vibration system is capable of producing 103,356 - 207,414 kg/m^2 of contact pressure. Approximately 60 - 70 passes per lift were required to produce the desired compaction.

In order to reduce the possibility of damage to the PVC liner the skid-loader was filled with sand and used to compact nearby all side and end walls. Also, a plastic strip was fastened along all sides to act as an anti-seep collar. The strip, extended approximately 15 cm into the cell, was used to preclude side wall seepage.

A mobile soil testing lab was received on loan from the Engineering Transportation Research Laboratory at the University of Kentucky. This facility enables rapid determination of soil moisture. The standard oven drying procedure was replaced by a microwave oven to obtain a rapid response. Six nuclear density tests were taken per lift at both the 10 and 15 cm depths. Ten cylinder tests and two sand cone tests were also employed for each lift.

A drill rig was supplied by the Civil Engineering Department to remove cores from each cell for in-lab permeability analysis and subsidence studies. The permeability of a Type CH clay under optimum compaction is expected to range from 10^{-8} to 10^{-10} cm/sec. Thus, the perspectives for a highly impervious clay liner are excellent.

An apparatus designed specifically for the measurement of permeabilities of fine-grained soils (clays) has been constructed (1983) in the Daniel V. Terrell Soils Laboratory of the Department of Civil Engineering at the University of Kentucky. The apparatus is constructed primarily of stainless steel components, is capable of operating at pressures up to 100 psi, uses a triaxial type of chamber with upflow of the permeant, and has computerized data collection and analysis. These features have been incorporated due to some of the inherent difficulties with performing permeability tests on clays. Some typical problems are air entrapment in the soil sample, long test times, and having high back pressure. Automated data collection help to alleviate these problems. Three samples can be tested simultaneously.

The permeabilities of the clays taken from the covers will be tested using this apparatus. In addition, samples have been obtained from which horizontal permeabilities can be determined. Recompacted samples will also be tested to ascertain the effect of different moisture contents and densities on the permeability. Some field tests are planned and will be compared to the laboratory results. This information will be provided for input to the models being used to describe the hydrologic effectiveness of the landfill cover.

The Pervious Layer

Perforated PVC drains, wrapped in Fibretex fabric, were installed on top of the clay layer. These drains are employed to increase water movement along the pervious sand layer. As with the leachate collection system, the first two drains, located at the 9 and 18 m marks, can be plugged and the efficiency of a 27 m drain spacing can then be evaluated. Another alternative would be to plug all drains, which would allow evaluation of saturated conditions.

A 0.6 m sand layer was placed above the three drains. This pervious layer is used to relieve pressure above the clay layer. As before, multi- sensor instrumentation was located above and below the clay/sand interface. All sand was placed by the skid-loader.

Surface Layer

Instrumentation was located above and below the sand/topsoil interface. The topsoil was placed by the skid-loader in approximately one 0.6 m lift and tilled to prepare a seedbed. Care was taken not to compact the topsoil layer, in order to obtain a bulk density of 1.4 - 1.5 gm/cm^3. Such a bulk density is representative of topsoil conditions commonly found in the field.

Surface drains of either half-round pipe or fabricated metal troughs were placed across the cell width at 9, 18, and 27 m from the farthest upslope position (Figure 2). Flow from these surface drains is directed towards the instrumentation pits and measured by tipping buckets. Rainfall shields were placed above all surface drainage pipes to intercept rainfall falling directly into the pipes and to direct this precipitation off the cell.

INSTRUMENTATION

Overview

Standard soil characterization equipment was used for initial soil testing. In-place density was obtained from the nuclear density device, sand cone, and sand cylinder apparatus. Permeability is being measured by a high pressure triaxial chamber with permeant upflow provisions.

In-field instrumentation includes soil moisture measuring devices, temperature probe, and flow measuring equipment.

Soil Moisture Devices

Soil moisture is being determined from: (1) tensiometers, (2) gypsum (resistance) blocks, and (3) neutron probe. The tensiometers are specially constructed to yield relatively rapid response. Standard porous cups (1.9 cm diameter , 7 cm length) were attached to 0.32 cm diameter nylon tubing. The narrow tubing significantly reduced water volume and thus yielded a more sensitive response.

Tensiometers were placed along with gypsum blocks and thermocouple wire at six locations in each cell (Figures 1 through 3). It is essential to determine soil moisture at each interface. Hence, sensors were placed 10 to 15 cm below and above each interface: (1) lower sand-clay, (2) clay-upper sand (pervious layer), and (3) sand-topsoil.

A soil moisture/tension relationship was determined for each soil layer through pressure-plate analysis. Thus the moisture percentage for each soil layer can be determined from tensiometer readings. Pressure gauges were mounted in the instrumentation pits for subsequent data recording.

Tensiometers have a relatively limited range of sensitivity, approximately 3,100 to 8,266 kg/m^2. Beyond about one bar (approximately 10,000 kg/m^2) the soil becomes too dry and air cavitation occurs, rendering the device useless. If actual soil moisture is above this level, the tensiometers operate reliably; otherwise, continuous priming, which moistens the area around the porous cup, is needed and data will reflect moisture forced into the soil via priming and not actual soil moisture movement through the multi-layered profile. It is also recommended that the tensiometer be drained during anticipated freezing conditions. Hence, if only tensiometers are used, winter data gathering would cease.

Gypsum, electrical resistance, blocks are highly absorbent. Two stainless steel probes are molded in the gypsum blocks and spaced such that a large resistance exists between probes. A low level AC voltage is applied to the probes; as moisture penetrates the gypsum material the resistance decreases, changing the voltage drop across the probes. This voltage drop is related to soil moisture content during block calibration, and is recorded by the data gathering electronics.

Due to the anticipated problems with tensiometers, a multi-sensor approach of soil moisture data gathering was initiated. Gypsum blocks were installed at each interface about 15 cm from the tensiometers at the identical horizontal level. A calibration curve was developed for each soil type which relates percent soil moisture to resistance. Such a curve is shown in Figure 5 for the clay layer. The effective range is 3,100 to 15,500 kg/m^2, that is, complete coverage of expected soil moisture levels in the multi-layered cover system. Gypsum

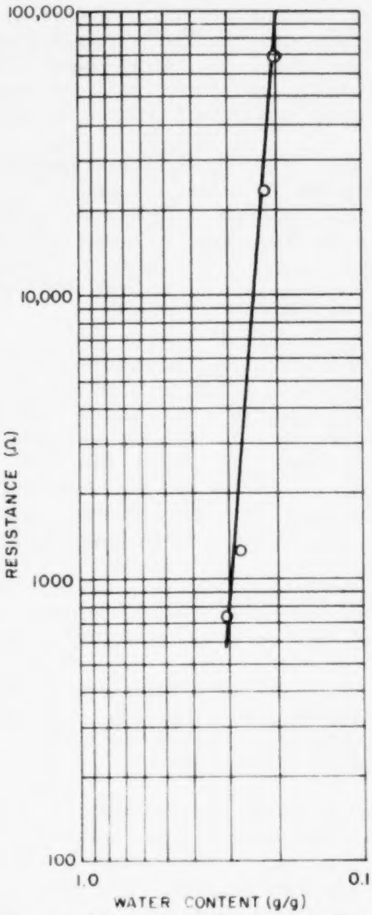

Figure 5. Calibration Curve for Resistance Blocks

blocks, thus calibrated, have several advantages: (1) year-round application, (2) a large range of soil tensions, (3) accurate conversion into soil moisture values, (4) direct recording of voltages via a data logger and micro computer, and (5) relatively rapid response.

Thermocouple wire was placed midway between gypsum blocks and tensiometers. The thermocouple sensor produced two major benefits: (1) extremely rapid response of temperature changes, and (2) information required for more precise determination of soil moisture by resistance blocks. The rapid response to a 0.1°C temperature change by the thermocouple often indicates the passage of a wetting front. Thus, the exact timing of a soil moisture front can often be determined.

Additionally, gypsum blocks are temperature sensitive and their resistance changes with temperature in a known manner. Thus, accurate measurement of the temperature increases the accuracy of gypsum block readings and associated soil moisture determinations.

A fourth soil moisture sensor, the neutron probe, was used to determine the spatial variability of soil moisture with respect to depth and areal coverage. Three access tubes were installed as illustrated in Figures 1 through 3. Use of the neutron probe allowed determination of soil moisture at 7.5 cm intervals throughout the multi-layered profile at three different locations. Such measurements expanded the data source by providing an estimate of the soil moisture throughout the profile. Such estimates are needed to determine the current status of the water balance and are necessary for predictive modeling.

Flow Measurements

Flow from all 27 drains was directed to 27 tipping buckets. The sizing of tipping buckets was based upon expected maximum flow rates from the various levels. Tipping buckets for the leachate collection system are 30 ml per tip. Flow from the pervious layer drains is directed to 300 ml/tip devices and surface flow is routed to 450 ml/tip tipping buckets. Thus, runoff from the 5 yr-1 hr event, under average soil moisture conditions, can be accounted for by this tipping bucket design. As can be seen from Figure 3, all drainage enters instrumentation pits, is measured by individual tipping buckets, and discharges via a common exit to a grass waterway.

All tipping buckets were designed with three adjustments to allow for extremely accurate calibration and flow measurements. Calibration of the largest 18 tipping buckets was based on known volumes of flow from various orifice sizes maintained at a constant head and a prescribed fall distance between the orifice outlet and inlet tray of the tipping buckets. The smaller tipping buckets were calibrated using the smallest available orifice size and use of a 50cc syringe.

Due to the several adjustments built into the design of these tipping buckets and the extensive calibration program, the tipping buckets were found to have an accuracy of ± 0.5 percent. This contrasts with an expected accuracy of ± 10 percent for flume type devices.

Installation of Sensors

Soil moisture and temperature measuring devices were installed approximately 15 cm above and below each soil interface during construction of each layer. Also, sensors were placed approximately at mid-depth in the bottom sand layer in cells 2 and 3.

Installation of access tubes for the neutron probe was accomplished with minimal disturbance of the soil profile. Access tube placement commenced after compaction of the clay layer. The clay was augered using a bit with a diameter slightly less than that of the access tube. Following clay extraction, a pipe of the same diameter as that of the auger was driven to the sand layer. Water was added to the sand to assist in removal and then the pipe was driven to within approximately 45 cm above the liner. The pipe, containing compacted sand, was removed and the access tube of a slightly larger diameter was driven through the hole.

A pipe was inserted into the access tube and a machined steel point placed at the lower end of the pipe. Also, in order to drive the access tube without damage, an impact plate was machined and attached to the top of the access tube. The complete assembly was driven into the previous augered hole. Then the pipe assembly was removed for later use. An anti-seep collar booth was attached to the access tube slightly below the clay surface to prevent any piping effects. Finally, the remaining sand and topsoil layers were backfilled around the access tube.

A great deal of effort was exerted to place sensors during construction and to install access tubes without altering the influence of construction equipment upon the multi-layered cover. It is felt that the additional time and monies utilized to install such a multi-sensor system without any significant disturbance of the soil profile are worth the effort and should ensure an excellent data base.

Data Acquisition and Processing System

Compound Description

The major data acquisition and processing components consist of: (1) Campbell CR-5 data logger, (2) Tecmar Lab Master multiplexer, and (3) the IBM Personal Computer. The Campbell unit receives and stores temperature data from the 20 locations in the cells at hourly intervals and the Tecmar/IBM PC units receive, process, store, and analyze information from the tipping buckets and gypsum blocks.

The IBM Personal Computer is equipped with two dual-sided, dual density, 5¼ inch disk drives, and has 256K of Random Access Memory (RAM). It contains several expansion boards related to data acquisition. One is a Quadboard, manufactured by Quadram Corporation. It provides an additional 256K of RAM. The Quadboard also has a battery powered clock/calendar, which is used in conjunction with data analysis.

The PC-Mate Lab Master, manufactured by Tecmar, Inc., consists of a "mother board" located inside. The computer chassis and the "daughter board" are externally connected by a 50 ribbon cable. The Lab Master converts analog signals, in the form of voltages, to digital signals. The Lab Master only has pins for 16 analog to digital conversion channels to be read; with a multiplexer, it can handle up to 256 channels. Sixty are required for current applications.

The PC-Mate IEEE488 Interface Board, also by Tecmar, is connected to the Lab Master daughter board. The version of the IEEE488 used can multiplex 48 channels of information and sent it to the Lab Master. With the 16 channels the Lab Master can process, a total of 64 channels exist.

A Screw Terminal/Signal Conditioning Panel, manufactured by Data Translation, is connected to the IEEE488 by a 50 ribbon cable. The wires leading from the tipping buckets and gypsum blocks are connected to these screw terminals.

Application

The program driving these devices

scans all 27 tipping buckets in less than 1.5 sec. Minimum tipping rate of the buckets under the most intense design storm conditions is 1.7 sec. Thus, a complete scan is completed prior to subsequent bucket tipping. The resistance blocks are scanned at the same frequency as tipping buckets for efficient programming. Resistance block voltages are written to a disk with the associated time at five minute intervals.

The Campbell CR-5 data logger stores temperature, in °C, on a cassette tape. All systems have hard copy back-ups and are protected from voltage spikes by a power supply filter.

Rainfall Simulator

The rainfall simulator is a new, highly portable nozzle type simulator designed for erosion, infiltration, and runoff experiments.[1] The simulator is being modified, retrofitted, and calibrated prior to application on this multi-layered cover study. Major characteristics of the rainfall simulator are: (1) near natural rainfall drop-size distribution and drop inpact velocity, (2) spatially uniform rainfall intensity and drop-size distribution, (3) near vertical angle of drop impact, and (4) reproducible storm patterns, durations, and intensities. The rainfall simulator will be used to augment natural rainfall as required to stress the multi-layered cover system.

Lab Subsidence Study

The proposal for the EPA-sponsored study of the hydrologic response of hazardous waste landfill covers included an evaluation of these clay covers under subsidence conditions. In order to study this type of behavior under controlled conditions, a laboratory model of subsidence and cracking in a compacted clay layer was proposed. Several approaches used to physically model soil behavior have since been evaluated. The method of centrifugal modeling was chosen as the most appropriate for this study. Centrifugal modeling has been determined to be appropriate for simulating certain types of soil systems[2]. Centrifugal modeling consists of building models of the prototype structure at a reduced scale. The models are accelerated by rotating them in a centrifuge. This acceleration is expressed as a multiple of gravitational acceleration that represents a scaling factor which multiplies the reduced dimensions of the scale model and allows it to respond to loading conditions in the same way as the prototype. Centrifugal model behavior can accurately reproduce and predict prototype behavior if correct experimental procedures are used. Some advantages of this method include: the relatively small amounts of undisturbed soil that are required for model construction, the minimal effect of sampling on the prototype clay cover; and the acceleration of time effects, which allows for more experimentation in a given period of time.

Once this method of study was decided upon, the design and construction of a centrifuge capable of producing the required accelerations was begun. During the summer of 1983, a 1.83 m diameter centrifuge was assembled that is capable of accelerating a 27 kg sample to 100 G. It is constructed of steel tubing and is secured to a 0.6 m thick reinforced concrete floor for stability. The centrifuge is powered by a 2 HP electric DC motor with a controller capable of precise rotational speed selection. As a safety measure, a 0.9 m high sandbag wall has been constructed around the centrifuge.

The 0.6 m thick clay cover will be modeled using 2.5 cm thick layers of the same clay that was used to construct the full sized test covers. The models will be accelerated to 24 G, in the centrifuge. Thus, the 2.5 cm layer should behave in a similar manner to the 0.6 m layer. In order to accommodate the behavior of the full width of the test plot, the soil layers in the model will be circular with a diameter of 0.3 m. Soil samples will be supported on a rigid aluminum disk while being accelerated and mounted to the centrifuge in a cylindrical container made of plexiglas and aluminum. To simulate the existence of cavities under the clay layer, holes will be cut in the aluminum base plate. These holes will vary from 2.5 cm to 20 cm diameter and will simulate cavity diameters of 0.6 m to 4.88 m in the prototype.

This centrifugal modeling study has several objectives. The primary goal is to predict how the test plot covers will behave when cavities are created beneath them. This prediction will probably consist of an estimate of the maximum cavity diameter that can form beneath the surface without causing subsidence of the cover layer, and a qualitative estimate of the degree to which cracking vs. plastic deformation of the clay layer occurs when the critical cavity diameter is exceeded. In addition, recompacted clay samples will be accelerated to study the relationship between soil moisture content, compactive effort and the soil's ability to deform with cracking over a cavity.

RESULTS

The design and construction phases of this project have provided a valuable opportunity to describe and document a layered soil system, and the difficulties encountered in properly building this system. The multilayered, multi-sensor soil moisture monitoring approach, utilizing tensiometers, resistance blocks, thermocouple wire, and the neutron probe, will ensure an accurate measure of soil moisture movement throughout the soil profile. These sensors should provide a comprehensive data base for modeling efforts. Use of highly accurate tipping buckets can also assist in determining the economic feasibility of alternative drainage and leachate collection systems.

Although the initial construction phase of this project was not complete at the submittal time of this article, a limited amount of data collected from two storms monitored on the initially constructed cover appear to be extremely promising. Temperature readings from the thermocouples preceded increased moisture readings on the resistance blocks in the uppermost sensors. Using the resistance block, a rapid response of the passage of the wetting front by the thermocouples was detected, and accurate moisture changes were recorded.

ACKNOWLEDGEMENTS

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Investigations in this study are published by the permission of the Director of the Kentucky Agricultural Experiment Station and this study is designated as Article No. 84-2-17.

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ESTIMATION OF MAXIMUM COVER SUBSIDENCE EXPECTED IN HAZARDOUS WASTE LANDFILLS

William L. Murphy and Paul A. Gilbert
Geotechnical Laboratory
USAE Waterways Experiment Station
Vicksburg, Mississippi 39180

ABSTRACT

Numerical models were developed to simulate horizontally layered hazardous waste landfills. The models were analyzed using methods of linear elasticity to estimate the maximum amount of subsidence of the final cover to be expected after landfill closure and after deterioration of the waste containers. The landfill consisted of alternating layers of intermediate inert cover soils and steel drums filled with simulated waste materials. Waste drums, waste materials, and intermediate cover soils were assigned values of density, Young's modulus and Poisson's ratio for the analysis. Landfill geometry, layer thicknesses, waste drum placement, steel drum stiffnesses, and laboratory consolidation tests on the soils and simulated wastes were also considered. To simulate postclosure waste layer deterioration, compression of the fill was calculated for decreasing values of the Young's modulus of the waste layers. The analyses indicate that as much as 92 percent of the expected subsidence of the cover is caused by closure of cavities (void space) inherent in landfilling. The maximum expected subsidence was calculated to be approximately 12 percent of the total landfill thickness.

INTRODUCTION

Settlement of sanitary and low-level nuclear waste landfills with subsequent damage to the covers has been documented. The U. S. Environmental Protection Agency (EPA) is concerned that settlement/subsidence of hazardous waste landfills may produce similar problems with cover systems. Little or no documentation exists of the potential for settlement in and subsidence of the covers of hazardous waste landfills operating in accordance with EPA interim guidelines under the Resource Conservation and Recovery Act (RCRA). This paper presents the results of analyses of maximum subsidence expected to occur after deterioration of waste drums in a representative hazardous waste landfill. The analysis is part of a broader study conducted for EPA.

PURPOSE

The purpose of this study was to (a) determine the maximum amount of postclosure subsidence of a landfill cover that will occur after the waste containers (steel drums) have deteriorated and exposed their contents; (b) estimate the proportion of the total subsidence contributed by various landfill components; and (c) develop analysis and predictive techniques to estimate the ultimate postclosure cover subsidence to allow EPA to develop guidance for landfill operators to design final covers to withstand the stresses and the loss of runoff slope associated with subsidence.

APPROACH

Subsidence mechanisms postulated for similar and related geotechnical activities were assessed to develop the appropriate analytical approach. Several active and proposed hazardous waste landfills were observed so that a representative landfill could be developed for model analysis. Analysis of the representative landfill consisted of applying gravity loading to a filled and closed, horizontally layered, below-grade landfill. Total subsidence of the cover was determined by calculating the settlement of each fill layer for several decreasing values of elastic modulus applied to the layer materials. Waste drums, waste materials within the drums, and inert fill (soil) comprising intermediate layers between layers of drums were assigned values of density, Young's modulus, and Poisson's ratio in the analyses. Landfill geometry and layer thicknesses were also considered. Estimates of steel drum stiffness were made from existing data. Moduli of intermediate cover soils and of simulated drum contents were derived from existing data and from laboratory one-dimensional consolidometer tests, respectively.

THE LANDFILL MODEL

The landfill configuration chosen for analysis is shown in Figure 1 (the configuration for drums placed on their sides is shown). The excavation is 50 ft deep, 200 ft wide at the base, and has side slopes of 1 vertical on 3 horizontal. The final cover has approximately 5 percent (1 vertical on 20 horizontal) slope from the crown to the original ground surface. The total thickness at the center of the landfill is 62 or 62.5 ft, depending on the drum configuration. The landfill is lined with compacted clay 8 ft thick at the base and 5 ft thick on the sides and in the cover. The 55-gallon drums containing the waste material are placed across the fill in continuous horizontal layers, which are 2 ft thick for drums on their sides and 3 ft thick for drums on-end. Waste layers alternate with layers of intermediate soil cover 1.5 ft thick. Cavities inherent from the drum placement geometries exist within the fill.

The liner, final cover, and intermediate cover are a clay with known laboratory-tested properties determined for a representative model material, the "Vicksburg buckshot clay," with Atterberg limits similar to liner clays of actual landfills (see Table 1). The liner and final cover clays are compacted; the internal intermediate cover soil is not compacted. The simulated waste in the drums was a commercial absorbent, noncalcined crushed calcium bentonite claystone, which was soaked in water for 48 hours to better simulate in-place waste materials. (Clays fired at 1200°F are said to be "calcined"; clays fired at lower temperatures are said to be "noncalcined.")

ANALYSIS OF POSTCLOSURE SUBSIDENCE

Assumptions

In order to estimate the maximum or worst case subsidence to be expected, it was assumed that no filling of cavities inherent from drum placement occurred by downward sifting of intermediate cover soils, and that the cavities ultimately close completely. The analyses show that as much as 92 percent of the ultimate subsidence can be attributed to closing of the inherent cavities. The remaining subsidence is attributed to compression of landfill contents.

Other assumptions are: (a) all settlement occurring in the liner and intermediate cover layers is complete by the time the landfill is filled and closed, at which time the cover is rebuilt to accommodate any subsidence that has occurred; (b) the stress condition in the landfill at the end of filling is determined and does not change after closure of the landfill; (c) all postclosure subsidence occurs through closing of cavities and through compression of only the waste layers by degradation of the waste layers' elastic moduli; (d) maximum subsidence will, because the landfill is symmetrical about the central vertical axis, occur at the center of the landfill and can be determined by analyzing the settlement of a central, layered column; (e) stress is assumed to vary linearly with depth; (f) one-dimensional deformation occurs in the

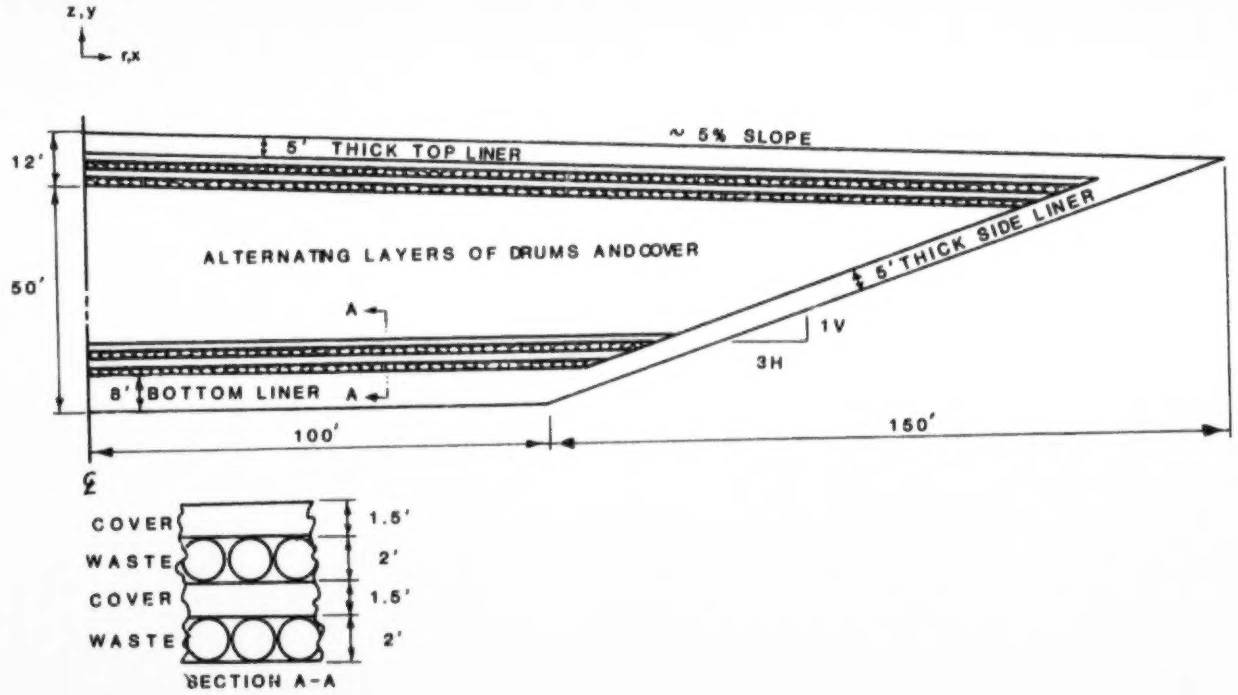


Figure 1. Assumed hazardous waste landfill configuration (shown for drums placed on their sides).

TABLE 1. ATTERBERG LIMITS OF TYPICAL HAZARDOUS WASTE INTERIM COVER MATERIALS

Site Location	Liquid Limit, percent		Plasticity Index, percent	
	Range	Average	Range	Average
Alabama	32-48	38	12-30	18
South Carolina	65-75	68	20-30	24
New York	46-54	50	26-33	30
Model material (Vicksburg buckshot clay)	56		34	

central column; (g) each landfill layer is homogeneous and isotropic and can be represented by a single material with composite properties; and (h) the fill is not saturated.

In equation form, total subsidence, δ_T, may be represented as

$$\delta_T = \delta_{ISL} + \delta_{LV} + \delta_{DV} + \delta_{\Delta E} \qquad (1)$$

where

δ_{ISL} = subsidence due to consolidation of the intermediate cover layers

δ_{LV} = subsidence due to closing of the inherent geometric layer void space

δ_{DV} = subsidence attributed to void space inside the drums. This component is assumed to be zero, but should be quantified and accounted for in a general approach

$\delta_{\Delta E}$ = subsidence due to change in stiffness of the waste layers

Settlement by Closing of Cavities

The maximum volume of void, or cavity, that can be included in the landfill by drum placement may be calculated geometrically for drums placed on their sides and for drums placed on end. The maximum cavity volume for the former is 10.73 percent of the total landfill volume and for the latter is 9.31 percent. If the cavities close completely, the maximum total subsidence must be the sum of cavity closure plus subsidence by compression of the landfill contents. However, actual landfill operations will reduce maximum cavity volume because the operations do not achieve perfect drum placement and because filling of interdrum space by sifting of cover soils during filling is generally practiced to some extent. Conversely, any unexpected void within the drums would contribute to the volume of inherent cavity.

Equations for Settlement by Compression of Waste Layers

An equation was developed using the methods of linear elasticity to calculate settlement of the waste layers after closure for decreasing values of the Young's modulus of the waste layers. The subsidence in the cover is assumed to be the cumulative settlement of all the waste layers within the landfill. The equation is

$$\Delta L = \frac{\gamma L^2}{2} \left(\frac{1+\nu}{1-\nu}\right)\left(\frac{1-2\nu}{E}\right) \qquad (2)$$

where

ΔL = the change in length of the analyzed column of waste

γ = the density of the composite waste layers

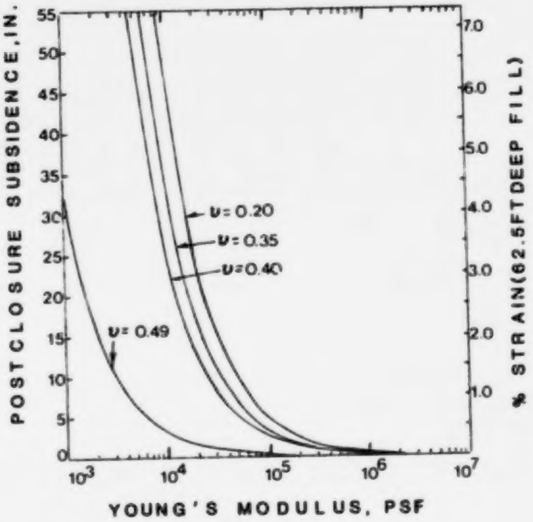
L = the cumulative length of the waste layers, i.e., the waste column

ν and E = Poisson's ratio and Young's modulus, respectively, assigned the composite waste layers.

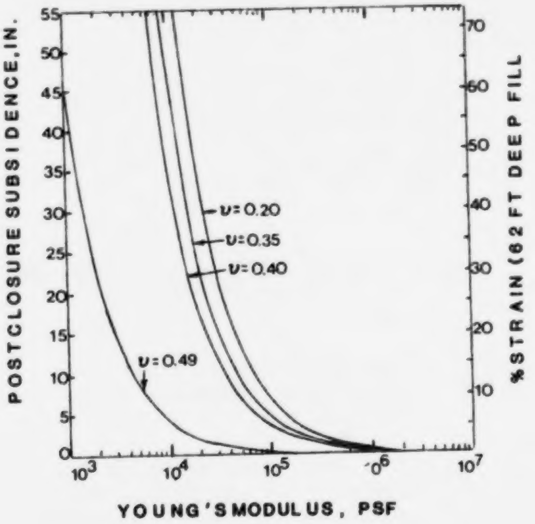
The analysis proceeds by applying gravity to the column and calculating ΔL for successively lower values of E and for several values of ν. Families of curves were plotted for the two drum placement configurations shown in Figure 2. Two families of curves are needed because the value of L in Equation 2 is different for the two drum configurations (i.e., 14 waste layers or 28 ft total waste layer thickness for drums placed on their sides; 11 layers or 33 ft total waste layer thickness for drums placed on end). Figure 2 shows that deformation increases rapidly as the modulus falls below about 100,000 psf. Ultimate subsidence can be estimated using the curves of Figure 2 if values of E are known for the initial condition (immediately after landfill closure) and final condition (after complete waste drum deterioration). The ultimate subsidence is the difference between the subsidences for the initial (intact drum) and the final (deteriorated drum) conditions. Use of the curves in this way simulates the deformation or settlement of the landfill contents after closure.

Estimation of Subsidence for Representative Waste Layers

The waste layer for drums placed on their sides is a composite of steel drum, drum contents (the soaked calcium bentonite claystone), and that portion of the space between the drums that is filled with intermediate cover soils during landfilling. The composite Young's modulus for the intact drums placed on their sides (the initial condition) must be comprised of the



A. Drums Placed on Their Sides



B. Drums Placed on End

Figure 2. Postclosure subsidence prediction curves for compression of waste layers by decrease in elastic modulus.

modulus of the steel drum (a steel cylinder on its side) and that portion of the intermediate cover soil in the space between the drums. The composite intact-drum waste layer modulus can be determined using the relationship

$$E_{Ti} = \frac{4E_D E_s}{\pi\ E_s + 4E_D\ (1/2-\pi/8)} \qquad (3)$$

where

E_{Ti} = elastic modulus of the initial composite waste layers, psf

E_D = modulus of the steel drum

E_s = elastic modulus of the intermediate cover soil, psf

The E_s was determined from consolidation tests on the model intermediate cover soil. The composite intact-drum waste layer modulus for an E_s of 1.04×10^5 psf and an E_D of 9.7×10^6 psf is, from Equation 3, 9×10^5 psf. This modulus corresponds to an initial subsidence of approximately 0.37 in. for a Poisson's ratio of 0.35 in Figure 2a.

If the waste drums are allowed to corrode completely and expose the contents, the wastes are then subjected to compression, which is controlled by the modulus of the waste material. One-dimensional consolidation tests were performed on the noncalcined crushed claystone simulated wastes and on another commercial product, oil-spill absorbent (calcined crushed claystone), after allowing the materials to soak in water for 48 hours. Figure 3 presents the results of the consolidation tests in the form of constrained elastic moduli. The secant modulus of 40,000 psf (275 psi) of the noncalcined material was chosen to represent the model waste material (for final conditions) because it is the lower of the two and because it is commonly used in the disposal industry. As in the initial condition, the final composite waste layer modulus must be calculated, in this case from

$$E_{Tf} = \frac{4E_c E_s}{\pi E_s + 4E_c\ (1/2-\pi/8)} \qquad (4)$$

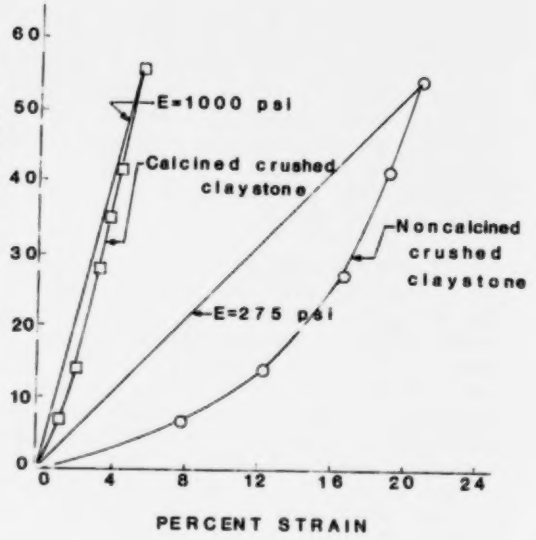


Figure 3. Constrained elastic moduli of two simulated waste materials from one-dimensional consolidation tests.

where

E_{Tf} = elastic modulus of the composite system in the final condition (steel drums corroded entirely away)

E_c = modulus of drum contents (the noncalcined material)

E_s = modulus of intermediate clay cover soil, as before

Note that Equations 3 and 4 are the same except that E_D of Equation 3 has been replaced by E_c in Equation 4, representing deterioration of the drum and exposure of the drum contents in the final condition. Substituting the modulus values for E_c (40,000 psf) and E_s (104,000 psf) into Equation 4 yields a corresponding composite modulus of 48,000 psf, which represents a final condition subsidence on Figure 2a of 7 in. (with $\nu = 0.35$). Subtracting the initial value of 0.37 in. from the final value of 7.02 in. yields a corresponding value of 6.65 in. or 0.89 percent for subsidence by compression of cell contents for drums placed on their sides in a landfill 750 in. (62.5 ft) thick. The subsidence possible from closing of inherent cavities is 10.73 percent, and the ultimate maximum expected subsidence is the sum or 11.62 percent (approximately 87 in. for the modeled landfill).

A similar analysis can be performed for a landfill with drums placed on end. The effective elastic modulus of a hollow steel cylinder carrying all of the axial load can be shown to be $E_D = 3.86 \times 10^7$ psf , which is an initial modulus corresponding in Figure 2b to essentially zero subsidence. When the drums have completely corroded, the final modulus (drum content alone) is 40,000 psf, which corresponds to a final subsidence value of 11.70 in. (Figure 2b), or 1.57 percent strain in a height of 744 in. (62 ft). The subsidence possible from the closing of inherent cavities is 9.31 percent, and the ultimate maximum expected subsidence for drums placed on end is 1.57 + 9.31 or 10.88 percent (approximately 81 in.). These subsidence values would result in a final average cover slope of about 2 percent, which would be unacceptable under current RCRA guidelines, assuming the original slope was 5 percent.

CONCLUSIONS

Analysis of simulated hazardous waste landfills indicates that most (approximately 86 to 92 percent) of the fill settlement and corresponding cover subsidence can be attributed to the closing of inherent cavities in the fill. The remaining deformation is attributed to compression of wastes after deterioration of steel drum containers. The source of the cavity volume within the landfill is presumed to be unfilled space between waste containers (primarily steel drums). The landfill operator can substantially reduce the ultimate expected subsidence by striving to fill the interdrum space during operations. There appears to be no appreciable advantage of one drum placement configuration over another. If the maximum predicted subsidence should occur, the cover slope will be reduced below the recommended value. The settlement/subsidence operation from which the prediction curves for this study were produced can be applied to representative hazardous waste landfills having any depth, material densities, and elastic moduli.

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PERMEABILITY CHARACTERISTICS OF FLEXIBLE MEMBRANE LINERS MEASURED IN POUCH TESTS

Henry E. Haxo, Jr., Nancy A. Nelson
Matrecon, Inc.
Oakland, California 94623

ABSTRACT

Permeability characteristics of a variety of thermoplastic and partially crystalline membrane materials to several waste and test liquids have been explored in pouch experiments. These liquids include aqueous salt solutions (such as sodium chloride and lithium chloride), organic solvents (acetone and xylene), mixtures of acetone and water, several waste liquids, and water- and organic-soluble dyes that have been either suggested for use or used for detecting leaks in membrane liners in service. The pouch test involves sealing a quantity of waste or test liquid in containers that are fabricated of the membrane under test. The pouches are immersed in deionized water or other liquid. Transmission through the walls of constituents either inside or outside the pouch is monitored by changes in the weight of the filled pouch, chemical analysis, pH, and electrical conductivity of the outer liquid, and the appearance of the dyes in the outer liquid or on the pouch surface. Transmission rates for various components of the liquids through the wall can be calculated from concentration data.

Results of the pouch experiments show the permeability of polymeric membranes to water, some organic liquids, e.g. oils, acetone, and xylene, organic dyes, and hydrogen and hydroxyl ions, but not to other inorganic cations and anions. The results also indicate that the principal driving force in the transmission of the various species is the concentration gradient across the pouch wall membrane.

With additional development the pouch procedure appears to be a feasible and practical method for assessing the permeability of membrane liners to different molecular species under conditions that simulate some aspects of actual service, and for assessing the compatibility of a liner with a specific waste.

INTRODUCTION

The low permeability of flexible polymeric membranes to gases, liquids, and vapors makes this type of liner the best approach to meeting the requirements of the U.S. Environmental Protection Agency's regulations for the lining of waste storage, treatment, and disposal facilities to prevent the migration of waste liquids into the groundwater. This low permeability makes it impossible to test polymeric membranes by conventional methods used for soils and other porous materials. In contrast to the porous structures of soils and concretes, polymeric membrane liners are nonporous.

Moisture vapor transmission, for instance, as measured in accordance with American Society for Testing and Materials (ASTM) Method E96, has been used as a test for the permeability of membranes. The conditions encountered by the membrane in such a test differ significantly from those encountered in actual service; thus, the permeability of membrane liners in service to waste liquids and dissolved components probably is not reflected by the water vapor transmission data. Other methods of assessing the permeability of liner materials were investigated. One of the most promising methods was a procedure in which a waste or test liquid is sealed into a pouch fabricated from the liner membrane under test and then placed in a container filled with deionized water or other standard liquid. Such an arrangement simulates some aspects of a liner in a surface impoundment containing a waste liquid. The permeation of dissolved constituents of the waste liquid through the wall can be followed by pH and electrical conductivity measurements of the water in the outer container; the permeation of water into the pouch containing waste liquid can be determined by monitoring the weight of the loaded pouch. Also, the organic constituents of the wastes that pass through the wall into the outer liquid can be followed by analysis of the outer liquid by gas chromatography.

This paper describes the pouch test and presents the results of using this type of test to assess some permeability characteristics of polymeric membranes. Results of some long-term tests of a variety of lining materials and several different waste liquids and test fluids are presented. Included are the results of tests with actual wastes used in our past liner research programs, salts, two organic solvents (acetone and xylene), and inorganic and organic tracers.

OBJECTIVES

The two main objectives of this study were:

1. To determine under conditions that simulate actual liners in service some of the permeability characteristics of polymeric membrane lining materials to constituents found in waste liquids that may be stored, treated, or disposed of on land.

2. To assess the permeability characteristics of polymeric membranes to a variety of test liquids and selected wastes using a pouch test.

METHODS AND MATERIALS

Polymeric Membrane Liners

The polymeric membranes that were fabricated into pouches and subjected to permeability studies in this work are listed in Table 1. All of the materials are thermoplastic or partially crystalline thermoplastics. Full descriptions of the individual materials and data on their properties are presented in Haxo et al (1982). Only one membrane in this study was fabric-reinforced, i.e. a chlorosulfonated polyethylene [CSPE (6R)]. Fabric-reinforced membranes were excluded to avoid possible pinholes or leaks caused by the threads. The principal objective of the program was to study the permeability characteristics of different polymeric compositions. Fabric-reinforced materials are included in later studies now in progress.

TABLE 1. POLYMERIC MEMBRANES[a] IN POUCH EXPERIMENTS

Polymer	Abbreviation	Liner serial number	Thickness, mil	Type of composition[b]
Chlorinated polyethylene	CPE	77	30	TP
		86	22	TP
Chlorosulfonated polyethylene	CSPE	6R[c]	31	TP
		55	35	TP
		85	33	TP
Elasticized polyolefin	ELPO	36	22	CX
Polybutylene	PB	98	8	CX
		221	30	CX
Polyester elastomer	PEEL	75	8	CX
Polyethylene, low-density	LDPE	21	10	CX
Polyethylene, high-density	HDPE	184	30	CX
high-density PE-EPDM alloy	HDPE-A	180	20	CX
Polyvinyl chloride	PVC	11	30	TP
		17	20	TP
		19	22	TP
		59	33	TP
		88	20	TP
		93	11	TP
		137	30	TP
	PVC-OR[d]	146	30	TP

[a] Details given in Haxo et al, in draft, and SW870, Revised (Matrecon, 1983).

[b] TP = thermoplastic, CX = partially crystalline thermoplastic.

[c] Fabric-reinforced with 6 x 6 nylon scrim.

[d] OR = Oil-resistant.

Waste and Test Liquids

A wide variety of test liquids were included in this study. They included actual waste liquids, several salt solutions, e.g. NaCl and LiCl, organic solvents, and various solutions containing dyes. Table 2 lists the wastes and test liquids in the study and presents some information regarding each.

TABLE 2. WASTE AND TEST LIQUIDS IN POUCH EXPERIMENTS

Type	Name	Matrecon waste number	pH	Electrical conductivity µmho/cm	Reference
Waste liquids					
MSW leachate	...	W-1	5.2	1,500	Haxo et al, 1982, p. 98
Acidic waste	"HNO_3-HF-HOAc"	W-9	1.1	155,000	Haxo et al, in press
Alkaline waste	"Slopwater"	W-4	12.0	129,000	Haxo et al, in press
Test liquids					
Brine	5% NaCl solution	W-19	...	62,000	
LiCl solution	5%	...	4.8	68,000	
LiCl solution	10%	...	4.6	106,000	
Organic-ketone	Acetone with dye[a]	...	...	...	
Organic-water mixture	50:50 acetone: water with dye[b]	...	...	...	
Organic-hydrocarbon	Xylene with dye[a]	...	...	...	
Tracer dye in DI water	1% Fluorescein solution	...	7.9	6,400	
Tracer dye in DI water	1% Sevron Red solution	...	2.4	660	

[a] 1% solution with Automate Red or with Fluorescent Yellow.

[b] 1% solution of methyl violet.

Description of the Pouch Test

In the pouch test, which simulates some conditions of liners in service in surface impoundments, small containers are fabricated of the membrane to be tested and are filled with waste liquid or other test liquid, sealed, and wholly immersed in a liquid of known composition, e.g. deionized water. Permeabilities of the membrane to water and to the dissolved constituents can be determined by observing with time the change in the weight of the pouch and changes in the pH, electrical conductivity, and the composition of the outer (originally deionized) water. Because of differences in the concentrations of different species across the membrane wall, osmosis will cause the outer water, which is higher in water concentration than the pouch liquid, to enter the pouch and also cause ions and dissolved constituents of the pouch liquid in which the concentrations are higher to tend to leave the pouch and enter the outer water. These effects are illustrated schematically in Figure 1.

During monitoring the pouch is weighed; however, an increase in weight of the pouch may only reflect absorption of the outer water by the wall and not permeation of water into the pouch. When the test is completed the pouch and its contents are weighed separately to determine the actual amounts that have been absorbed by the wall and the amounts that have permeated the pouch wall. The pouches are dismantled and the walls are analyzed for changes in composition, e.g. volatiles and extractables; physical properties, e.g. tensile and tear properties, are measured to determine the effects on the liner of one-sided exposure of the membrane to the waste.

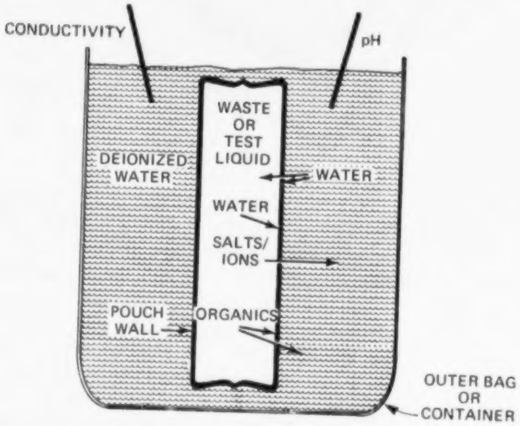


Figure 1. Pouch assembly with an aqueous waste or test liquid to show the movement of waste constituents during the pouch test. The filled pouch is immersed in deionized water. Arrows indicate the flow of specific constituents.

Results reported in Haxo et al (1982) show the feasibility of a pouch-type test for assessing simultaneously the permeability of polymeric membranes to wastes and to some waste constituents and the effects of one-sided exposure to a waste liquid on the physical properties of the membrane.

Mechanism of Flow Through Polymeric Membranes

In contrast to soils and other porous materials, polymeric membrane liners are nonporous. In soils the flow of liquids containing dissolved constituents is through the pores with hydraulic gradient the principal driving force. In the case of the membranes that are nonporous, flow of the fluid, be it gas, liquid, or vapor, proceeds essentially in three steps:

1. Dissolution of the fluid in the membrane.
2. Diffusion of the fluid through the membrane.
3. Evaporation of the fluid on the downstream side of the membrane.

Step 1 depends upon the solubility of the fluid in the membrane and relative "activity" of the fluid on both sides of the interface. The diffusion through the membrane in Step 2 involves a variety of parameters which include the molecular size of the permeating fluid and various characteristics of the membrane compound, e.g. presence of fillers, crystalline zones, crosslinks, etc. Step 3 is similar to the first step and depends upon the relative "activity" of individual constituents on both sides of the interface.

Overall, the major driving force for the movement of a given constituent is the relative concentration on both sides of the membrane. Each constituent in a mixture will tend to move from a higher concentration of the specific species to a lower concentration of that species. The placing of a waste in a pouch immersed in deionized (DI) water creates a significant concentration difference which will cause the movement of water and other waste or test liquid constituents.

Fabrication and Filling of Pouches

For the pouch test to be effective, the seams must be liquid-tight so that whatever passes in or out of the pouch passes through the walls. The thermoplastic and partially crystalline membranes can be heat-sealed which is the most effective method of making small seams; such seams require the least area and, if well made, have held up for the duration of exposure. A portable heat-sealing unit, designed primarily for sealing films less than 10 mil in thickness, was used in this study. Consequently, some problems were encountered in seaming the thicker membranes used for liners. Longer dwell time, greater pressure, and higher temperatures were needed to make seams of the thicker materials. Some seams of thermoplastics were made with adhesives and solvents.

Adequate pouch seams of crosslinked membranes could not be made with the two-part room temperature curing adhesives supplied by the manufacturers; thus, only pouches of thermoplastic and crystalline membranes were included in this study. Nevertheless, the general permeability characteristics determined for polymeric membranes are valid unless crosslinking is a factor.

A variety of pouch shapes were used during the course of this study. Figure 2 is a schematic of the pouch assembly used for most pouches. The dimensions of the individual pouches varied somewhat; some of the first pouches were 18 x 14 cm, which gave an effective wall area of approximately 500 cm^2 in contact with the pouch liquid. For the sodium chloride solution, the pouches were 17 x 12 cm between seams which yielded an effective surface of approximately 400 cm^2. For the experiments with solvents and the studies of tracer chemicals smaller pouches were used which could be placed in closed quart jars. Also, smaller pouches made of high density polyethylene (HDPE) and other crystalline polymers were used because of the stiffness of these sheetings.

As is shown in Figure 2, most of the pouches included a neck through which the test liquid could be introduced and which could then be sealed. Figure 3 shows a pattern used for cutting and seaming the pouches made of the more flexible sheetings. The seams were tested by filling the pouches with water and checking for leaks after several days. To simulate extended exposure in a moist environment some of the pouches, i.e. those that were filled with the highly acidic waste (W9), were first immersed for two weeks in water at 70°C; for some pouches it was necessary at 70°C to put water in the pouch to prevent the pouch walls from sticking together. The soaking of the pouches at 70°C further tested the integrity of the seams. After a pouch was filled with the test liquid, as much air as possible was removed from the pouch and the neck was sealed; care was taken to keep the inside of the neck dry to insure a good seal. The volume of waste liquid added to the individual pouches varied from 30 to 200 mL, depending on the size and configuration of the pouch. Most of the pouches were heat-sealed and the rest were sealed with either an adhesive or a solvent.

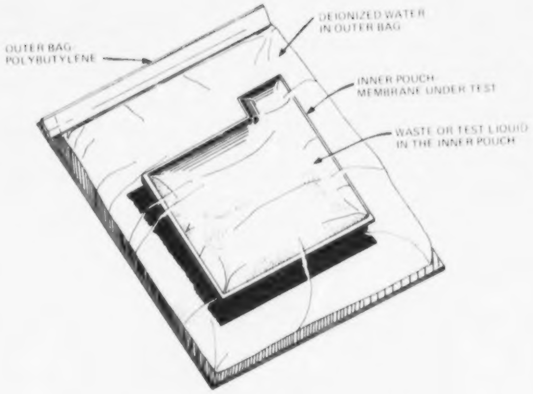


Figure 2. Schematic of pouch assembly showing inner pouch made of membrane material under test. The pouch is filled with waste liquid and sealed at the neck. The outer polybutylene bag, which can be easily opened, is filled with deionized water. For this configuration the water in the outer bag is monitored for pH, conductivity, and odor; the pouch is monitored for weight change.

Monitoring the Pouches During Exposure

To monitor the pouch assemblies, the following tests were performed periodically during the exposure:

1. The water in each of the outer bags was tested for pH, electrical conductivity, and odor, e.g. butyric acid, as in the case of tests with MSW leachate.

2. The pouches containing the test liquids were removed from the outer water, wiped dry, inspected for possible leaks, and weighed.

Figure 4 shows the pouches, the tray assembly for holding the pouches, and the auxiliary equipment for monitoring the pouches.

During the exposure, evaporation caused the water level in some of the outer bags to drop and expose the top part of the pouch to air; the loss was made up with deionized water. Also, if the concentration of ions in the water in the outer bag (as shown by electrical conductivity) appeared to be too high because of migration or possibly a leak, the outer water was replaced with deionized water. This would return the concentration gradient across the membrane essentially to its original value and increase the transmission rates.

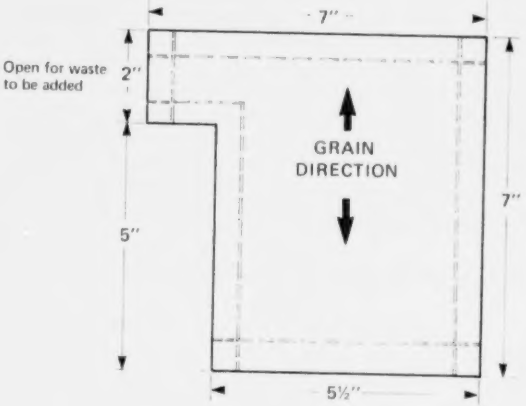


Figure 3. Pattern for cutting pieces of membranes for making some of the pouches. Dotted line indicates the heat-seal of the pouch. The inside dimensions of the pouch are 4.5 in. x 5.75 in. (11.43 x 14.6 cm), which yields an effective area (2 sides) of about 52 in.^{2} (335 cm^2).

Dismantling the Pouches After Exposure

Most of the pouches were allowed to continue their exposure for comparatively long times in order to assess the effects of exposure to water and wastes. If a leak developed in the pouch, as indicated by abrupt changes in the monitoring data, the pouch was withdrawn from exposure and emptied, and the liner and liquids were tested.

Dismantling most of the pouches involved the following steps:

1. Weigh the filled pouch.
2. Determine pH and electrical conductivity of the water in the outer bag.
3. Measure length and width between seams of pouch.
4. Empty pouch and weigh contents.
5. Determine pH and electrical conductivity of waste removed from pouch.
6. Dismantle pouch at seams, leaving bottom seam intact for measurement.
7. Blot the pouch dry and weigh to determine weight increase.

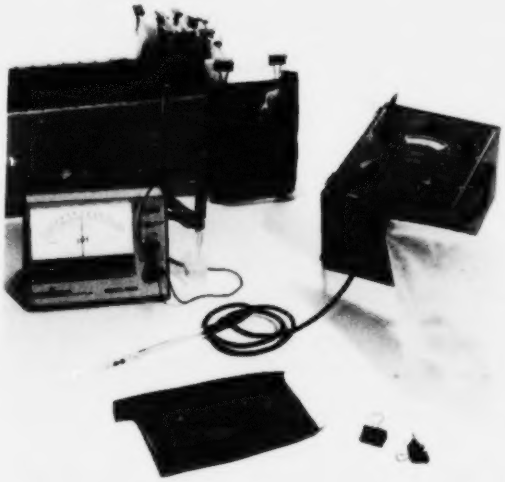


Figure 4. Pouch and auxiliary equipment for monitoring the pouches of polymeric membrane liners to assess permeability to water and constituents of waste liquids. Monitoring equipment for measuring pH and electrical conductivity of the water in the outer bags is shown.

Reporting the Results

The following results were reported for each pouch assembly tested:

1. Electrical conductivity and pH of water in outer bag as a function of time.

2. Weight of filled pouch as a function of exposure time.

3. Measurement of amount of waste liquid in pouch at start and at time of dismantling.

4. Analysis of waste in pouch, i.e. pH, electrical conductivity, and percent total solids, at beginning and end of exposure.

5. Analysis for volatiles and extractables of unexposed pouch membrane and pouch wall at time of dismantling.

6. Calculation of water transmission rate based on the early portion of the pouch weight-time curves. (Probably a better method for this calculation is to base it on the actual weight increase of the liquid in the pouch that is obtained when the pouch is disassembled at the end of the test.)

Table 3 shows the measurements that were regularly made initially, during monitoring, and at the time the pouches were dismantled. A few additional measurements were made such as chlorides content of the outer liquid in the case of the test of NaCl solutions.

TABLE 3. MEASUREMENTS MADE ON POUCHES AND CONTENTS

Parameter	Initial	Monitoring	Final
Weight of pouch (empty)	X	...	X
Weight of pouch (filled)	X	X	X
Weight of test or waste liquid in pouch	X[a]	...	X[b]
Pouch wall			
Extractables	X	...	X
Volatiles	X	...	X
Waste liquid in pouch			
Electrical conductivity	X	...	X
pH	X	...	X
Solids	X	...	X
Water in outer bag			
Electrical conductivity	X	X	X
pH	X	X	X
Solids	...	...	X

[a] Weight by difference in weights of filled and empty pouches.

[b] Weight by difference, as in footnote a, and by direct measurement of liquid at the time the pouch was disassembled.

Problems Encountered

Difficulty in Making Pouches with Cross-linked Sheetings

Unsuccessful attempts were made to fabricate pouches of crosslinked rubber sheetings, e.g. butyl rubber and neoprene, using two-part, room-temperature-curing adhesives supplied by the manufacturers. Seams 1.5 to 2 in. wide were made and appeared to cure; but, when the pouches were filled, the seams gradually opened and the pouches failed. Using the appropriate raw compound and high temperature and pressure, adequate pouches for testing can probably be fabricated from crosslinked membranes. For the initial purpose of this study, pouches made of thermoplastic sheeting were sufficient to demonstrate some of the permeability characteristics of polymeric membrane lining materials.

Failure of Pouches During Exposure

In spite of the testing of the pouches before filling with wastes, several of the pouches failed prematurely, after one to 872 days. All of the failures, except that of one polybutylene (PB) pouch, were in or at the seams. Those that failed at one and nine days were replaced. Also replaced after approximately 790 days was P30A which was made of elasticized polyolefin (ELPO) and filled with slopwater (W-4), the highly alkaline waste.

Seam failure appeared to predominate among the pouches made of thick membranes, seamed with solvents, or filled with slopwater. No seam failures occurred among the heat-sealed PB and polyethylene (PE) pouches. Seam failures indicate problems in the making of pouches; they do not reflect on the seaming by manufacturers of the liners, either in the factory or in the field. Since all of the heat-sealed pouches that failed were fabricated with a device that was not intended for seaming such thick materials, these failures can only reflect the inadequacy of the equipment.

RESULTS

Aqueous Sodium Chloride Solution

The first test solution explored in the pouch experiments was a 5% aqueous solution of sodium chloride which was loaded into pouches of chlorinated polyethylene [CPE (77)], CSPE (6R), ELPO (36), polyester elastomer [PEEL (75)], and two polyvinyl chlorides [PVC (11 and 59)]. Later, a second set of pouches was prepared and put into test. The second set consisted of membranes of CPE (86), CSPE (55), low-density polyethylene [LDPE (21)], PB (98), and two additional PVC's (17 and 19).

In the first set, three of the pouches failed when their seams opened; the remaining three were continued in test until they were dismantled after approximately 1152 days of exposure along with the second set which had been in exposure from 310 to 316 days. These pouch assemblies were subjected to the measurements described above. The results are presented in Table 4.

All of the filled pouches increased in weight during exposure though the amounts differed. In all cases but one, the liquids contained by the respective pouches increased in weight during the exposure. In several cases, the increases were caused by the absorption of water in the pouch

TABLE 4. POUCH TEST OF MEMBRANES WITH 5% SODIUM CHLORIDE SOLUTION AS THE TEST LIQUID

Parameter	CPE	CSPE	CSPE	ELPO	LDPE	PB	PVC	PVC	PVC
Matrecon liner serial number	86	6R	55	36	21	98	17	19	59
Liner thickness, mil	20	34	35	22	10	7	20	20	30
Pouch number	77	2	76	4	75	78	73	74	5
Days exposed	316	1151	315	1151	315	316	310	315	1115[a]
Area of pouch exposed to waste (original dimensions), m^2	0.0392	0.0408	0.0365	0.0408	0.0350	0.0375	0.0357	0.0351	0.0408
Weight of empty pouch									
Unexposed, g	40.00	45.33	62.90	23.39	12.41	7.48	35.30	32.80	47.24
After exposure, g	43.60	52.30	68.25	23.40	12.45	7.62	34.90	32.20	47.43
Change from unexposed, g	3.60	6.97	5.35	-0.01	0.04	0.14	-0.4	-0.6	0.19
Weight of filled pouch									
At beginning of exposure, g	184.30	388.52	163.10	326.50	163.90	186.00	158.60	134.70	537.05
After exposure, g	188.32	398.75	167.80	328.82	164.75	186.65	165.05	136.47	548.05
Change in weight, g	4.02	10.23	4.70	2.32	0.85	0.65	6.45	1.77	11.00
Test liquid in pouch									
Weight at beginning of exposure, g	144.30	343.19	100.20	303.11	151.49	178.52	123.30	101.90	489.81
Weight after exposure, g	144.72	346.45	99.55	305.42	152.30	179.03	130.15	104.27	500.62
Change in weight, g	0.42	3.26	-0.65	2.31	0.81	0.51	6.85	2.37	10.81
pH after exposure	3.6	6.9	7.3	5.0	4.5	5.9	3.5	6.6	6.4
Electrical conductivity after exposure, μmho/cm	64,000	80,000(?)	63,000	60,000	67,000	63,000	64,000	62,000	62,000
Liquid in outer bag									
pH at conclusion of test	3.6	7.4	6.7	4.8	4.4	5.1	3.1	6.4	5.8[b]
Electrical conductivity at conclusion of test, μmho/cm	86	585	66	34	31	27	371	16	57[b]
Calculated concentration of NaCl[c], %	0.005	0.035	0.004	0.002	0.002	0.001	0.022	0.001	0.003[b]
Chloride content[d], ppm	4	29	3	3	3	190	27	2	(b)
Water transmission through pouch wall[e], $g/m^2/d$	0.291	0.069	-0.002	0.049	0.073	0.043	0.619	0.214	0.238
Water transmission into pouch[f], g/m^2/day	0.315	0.203	0.384	0.053	0.033	0.051	0.184	0.181	0.238
Electrical conductivity[g] of DI water exposed to pieces of sheeting, μmho/cm	325	87	110	61	93	47	220	33	26
Calculated concentration of NaCl[c] in DI water exposed to sheeting, %	0.019	0.005	0.006	0.003	0.005	0.003	0.013	0.002	0.001

[a] Pouch failed between monitoring at day 1115 and dismantling at day 1152. Data presented for the exposed pouch are for day 1115 except for the emptied pouch weight, weight of test liquid removed from pouch, and pH and electrical conductivity of removed test liquid.

[b] After failure, at day 1152 the outer water had pH = 5.4, electrical conductivity = 4500 μmho/cm, NaCl concentration = 0.280 %, and chlorides content = >1000 ppm.

[c] Based on data in Handbook of Chemistry and Physics, 63rd edition, p. D-261 (1982).

[d] Method of chlorides analysis: FHWA-RD-77-85 (Clear and Harrigan, 1977)

[e] Calculated from change in weight of waste in pouch at time of dismantling.

[f] Calculated from weight of filled pouch based on early portion of weight-time curves or on entire exposure.

[g] Conductivity of DI water in PB bags in which coupons of membrane liners had been immersed for 805 days.

walls. The rate of transmission of water into the pouches is reported in Table 4. The greatest transmissions were through the CPE, CSPE, and the PVC's; the lowest were through the partially crystalline membranes (ELPO, LDPE, and PB). Judging by the change in electrical conductivity of the liquid in the outer bags, a small number of ions may have passed through the walls of the fabric-reinforced CSPE and two of the PVC's. Most of the increases in conductivity were low and were probably the result of ions, e.g. sodium and chloride, leaching out of the membranes. Also, analyses run on the solutions indicated very small amounts of chlorides passing through the membrane walls.

Overall, these results show that all of the membranes are permeable to moisture to varying degrees and that the difference in concentration between the outer liquid and the salt solution in the pouches furnishes the driving force that causes the water to migrate into the pouches. The movement of the ions from the test liquid in the pouches into the outer liquid is minimal. More detailed accurate analyses of the outer liquid should be made.

Municipal Solid Waste (MSW) Leachate

The first waste liquid to be used in the pouch-liner permeability study was the MSW leachate generated in the landfill simulators used in the study of lining materials for MSW landfills (Haxo et al, 1982). The membrane liner materials in these tests were based on CPE (77), ELPO (36), PEEL (75), and PVC (11, 17, and 59).

After 500 days of exposure (Table 5) it was apparent that both the water and dissolved ingredients initially in the leachate had moved through the pouch walls. The electrical conductivity of the water in the outer bag increased, indicating the permeation of some ions from the leachate in the pouch into the deionized water. Also, the odor of leachate in the water in the outer bags indicated that some organic constituents in the leachate were permeating the pouch walls. An increase in the weight of the pouches containing leachate indicated movement of water through the walls into the pouches. In that series, the ELPO allowed the lowest transmission of water and dissolved components, and the CPE appeared to be the most permeable.

TABLE 5. CHANGES TO POUCHES CONTAINING MSW LEACHATE AFTER IMMERSION IN DI WATER FOR 500 DAYS

Pouch[a]			Original values		Values at 500 days		
Polymer	Liner number	Pouch number	pH[b]	Electrical conductivity[b], µmho/cm	pH[b]	Electrical conductivity[b], µmho/cm	Weight increase[c], g
CPE	77	14	5.7	5.2	6.5	124.0	4.74
ELPO	36	11	5.1	4.3	4.5	17.8	0.22
PEEL	75	13	4.0	20.5	6.4	50.0	2.95
PVC	11	9	5.8	6.0	6.0	32.0	1.12
PVC	17	10	5.0	13.3	2.8	325.0	1.37
PVC	59	12	5.7	5.9	6.3	23.2	1.21
Blank[d]	...	8	5.5	1.33	4.3	11.6	...

[a] Areas of the pouches exposed to the leachate ranged from 544 to 624 cm^2.

[b] pH and electrical conductivity of (originally deionized) water outside the pouches containing leachate.

[c] Weight increase of pouches containing leachate.

[d] PB outer bag with DI water only.

Pouches Containing a Highly Acidic Waste

The first set of pouches in this study that contained a hazardous waste were filled with the highly acidic waste "HNO_3-HF-HOAc" (W9) that was being used in a research project on liners for hazardous wastes (Haxo et al, in press). Six pouches were used, each of a different membrane---(CPE) 86, CSPE (85), ELPO (36), PB (98), PVC (19), and PVC (88).

Monitoring the Pouches During Exposure

Monitoring the pouch assemblies included weighing the pouches containing the waste liquid and measuring the pH and electrical conductivity of the water in the outer bags. In addition, the general condition of the pouches and the waters was observed. Deionized water was added when too much water had evaporated from the outer bag, and the outer liquid was completely replaced with DI water when the concentration of dissolved constituents appeared to have become too high and was slowing the transmission of these constituents into the outer liquid.

Selected monitoring data for Pouch 19 are presented in Table 6. The concentration of ions as a function of time was calculated from the electrical conductivity data based on the assumption that the ions were from NaCl. Monitoring data for the six pouches (including weights, pH, and electrical conductivity) are presented in Figure 5.

Dismantling of Pouches

Condition of the Pouch Assemblies--In this set of six pouches only the PB failed prematurely at 609 days and was dismantled and tested. The failure was caused by embrittlement and cracking resulting from exposure of the top of the pouch to light. The PB sheeting did not contain carbon black. The remaining five of the original six pouches survived to 1887 days of exposure, when they were disassembled so that the empty pouches and the contents could be weighed separately, the contents analyzed, and the properties of the pouch walls measured.

All of the pouches had more or less retained their original flexibility or had swollen and softened during the exposure period. The water in the outer bags had a chemical or acrid odor indicating migration of constituents from the waste liquid in the pouches to the water in the outer bag.

The CPE pouch (P19) appeared to be in good shape at the time of dismantling, although the seams were relatively easy to pull apart. The surface on the inside of the pouch was somewhat pitted and the membrane had swollen.

The CSPE pouch (P18) had blistered badly on one side even though the sheeting was not fabric-reinforced. The liquid contents of the blisters were removed with a hypodermic needle and analyzed for pH and electrical conductivity. The pH of the liquid in the blister was 1.35, and the electrical conductivity of a 1:1 dilution with deionized water was 12,400 µmho. The waste fluid had permeated the sheeting which, when pulled by hand, delaminated relatively easily in the area of the blisters.

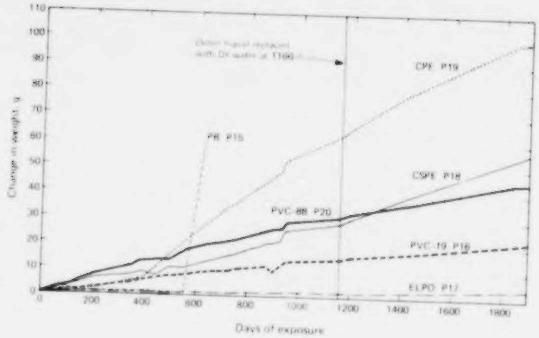
TABLE 6. MONITORING OF POUCH 19 (CPE 86) CONTAINING THE HIGHLY ACIDIC WASTE[a]

	Pouch	Outer water		
Days exposed	Change in weight, g	pH	Electrical conductivity, µmho/cm	Concentration[b], %
1	-0.70	5.9	8.5	0.0005
5	-0.52	6.0	14.8	0.0008
40	0.01	5.9	19.0	0.0010
93	0.65	5.8	23.4	0.0013
143	1.05	5.6	32.2	0.0018
386	6.78	2.7	420	0.026
500	15.78	2.0	3,550	0.22
552	20.28	1.6	5,500	0.34
625	26.58	2.2	6,300	0.40
790	38.27	1.8	8,500	0.54
900	46.38	1.8	9,900	0.65
949	52.34	1.8	12,300	0.80
1,160	62.98	2.1	14,600	0.95
1,169	(c)	(c)	(c)	(c)
1,174	...	3.1	350	0.022
1,199	65.43	2.6	900	0.054
1,427	79.68	2.0	4,000	0.25
1,887	100.00	1.8	5,900	0.37

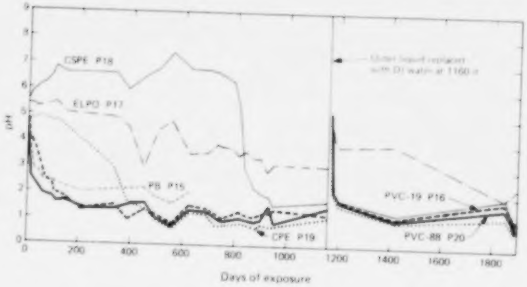
[a] "HNO_3-HF-HOAc", Matrecon waste W-9.

[b] Based upon the electrical conductivity of aqueous solutions of sodium chloride in Handbook of Chemistry and Physics, 63rd edition, p. D-261 (1982).

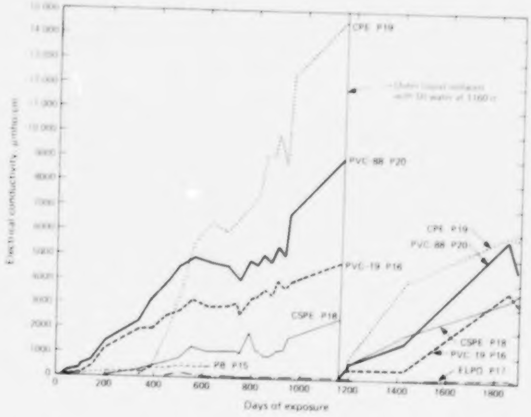
[c] Pouch rinsed, and liquid in outer bag replaced with deionized water.



a. Weight change in pouch.



b. pH of outer water.



c. Electrical conductivity of outer water.

Figure 5. Monitoring of pouches that contained the highly acidic waste, "HNO_3-HF-HOAc" (W-9).

The pouch made of ELPO (P17) retained its original condition well during exposure. It appeared to have changed little during the 1887 days of exposure.

The PB pouch (P15) that had failed at 609 days was dismantled at 625 days. It had cracked badly at the upper seam due to light degradation. The portion of the pouch that was below the water level of the outer bag appeared to have retained its flexibility and original properties.

The PVC (19) pouch (P16) was flexible but the inside was sticky. Also, the seams which had been made with a 50:50 solvent mixture of tetrahydrofuran and trichloroethane were easy to peel apart. The PVC (88) pouch (P20) had stiffened somewhat during exposure. The outside surface had become rough and discolored compared with the unexposed material. The inside was considerably more discolored and pitted, indicating some interaction between the membrane and the acidic waste liquid.

Weights--The various weights of the pouches and their contents are presented in Table 7. These data confirm the monitoring data; they show substantial increases in the contents of the pouches of CPE (P19), CSPE (P18), PVC (P16), and PVC (P20), further demonstrating the movement of water from the outer bag into the pouch due to the higher concentration of dissolved constituents in the pouch liquid.

The pH and electrical conductivity measurements of the water in the outer bags also show the movement of the hydrogen ions out of the pouches into the water in which the pouches were immersed. This result is confirmed by the lower conductivity and higher pH of the waste removed from the pouches at the end of the exposure compared with the waste placed in the pouches at the beginning of the exposure. The ELPO pouch had a particularly low permeability to water and the dissolved constituents of the waste.

Analysis of the Pouch and Outer Bag Contents--After the contents of the respective pouches were collected and weighed,

TABLE 7. POUCH TEST OF THERMOPLASTIC AND PARTIALLY CRYSTALLINE POLYMERIC MEMBRANES WITH ACIDIC WASTE, "HNO_3-HF-HOAc" (W-9) -- CHLOROSULFONATED POLYETHYLENE, CHLORINATED POLYETHYLENE, ELASTICIZED POLYOLEFIN, POLYBUTYLENE, AND POLYVINYL CHLORIDE

Data on Pouch and Waste Before and After Dismantling

Parameter	CPE	CSPE	ELPO	PB	PVC	PVC
Matrecon liner serial number	86	85	36	98	19	88
Liner thickness, mil	22	33	22	8	22	20
Pouch number	P19	P18	P17	P15	P16	P20
Number of days exposed	1887	1887	1887	609[a]	1887	1887
Area of pouch exposed to waste (original dimensions), m^2	0.0431	0.0484	0.0446	...	0.0443	0.0523
Weight of empty pouch						
Unexposed, g	39.17	59.03	27.32	8.24	33.24	31.68
Conditioned[b], g	57.44	79.46	26.70	8.82	34.09	33.45
After exposure, g	53.45	87.49	28.35	...	35.18	43.14
Change from unexposed, g	14.28	28.46	1.03	...	1.94	11.46
Change from conditioned, g	-3.99	8.03	1.65	...	1.09	9.69
Weight of filled pouch						
At beginning of exposure, g	250.22	261.93	128.31	122.98	176.60	189.47
After exposure, g	350.22	318.80	131.89	...	199.10	234.90
Change in weight, g	100.00	58.87	3.58	...	22.50	45.43
Waste contents of pouch						
Weight at beginning of exposure, g	192.79	182.47	101.61	114.16	142.51	156.02
Weight after exposure, g	291.49	229.04	103.01	...	163.54	191.86
Change in weight, g	98.70	46.57	1.40	...	21.03	35.84
pH after exposure[c]	1.10	1.00	0.95	...	0.90	1.05
Electrical conductivity[d] after exposure, μmho/cm	110,000	170,000	170,000	...	170,000	140,000
Liquid in outer bag						
Volume at conclusion of test, mL	375	395	520	...	463	400
pH at conclusion of test	1.80	1.95	3.25	3.0	2.0	1.85
Electrical conductivity						
Before water change[f], μmho/cm	14,600	2,500	92	...	4,800	9,000
At conclusion of test, μmho/cm	5,900	3,600	86	440	3,200	4,600
Water transmission through pouch wall[g], $g/m^2/day$	1.213	0.510	0.017	...	0.252	0.363

[a] Pouch failed due to cracking and embrittlement at upper seam caused by light degradation. Film was unpigmented, i.e. it contained no carbon black to absorb ultraviolet light.

[b] Empty pouches conditioned for two weeks in water at 70°C before waste added. Water added to CPE pouch (P19) after one week to prevent sides from sticking together.

[c] pH at beginning of test = 0.9.

[d] Electrical conductivity of waste at beginning of test = 200,000 μmho.

[e] The volume of liquid in the outer bag varied in the course of exposure due to evaporation. Deionized water was added periodically to cover the pouches.

[f] Outer liquid replaced with deionized water after 1169 days of exposure.

[g] Calculated from change in weight of waste in pouch at time of dismantling.

they were analyzed for pH and electrical conductivity. The results, also presented in Table 7, show a substantial increase in the volume and a significant decrease in the electrical conductivity of the waste in the pouch, indicating a dilution by the water that had entered through the pouch walls. Rates of transmission of the water into the pouches were calculated (Table 7). The calculations show the CPE to be the most permeable of the group and the ELPO the least permeable. Although the PB bag failed prematurely, the transmission value based on the weight gains was low.

These transmission values correlate well with the values calculated from the weight increases of the pouches during the exposure, but the fact that part of the weight increase is a result of the absorption of water by the pouch walls requires that the earlier values be corrected.

Highly Alkaline Waste Liquid

Pouches fabricated from six different membranes, CPE (77), CSPE (85), ELPO (36), PB (98), and two PVC's (19 and 88) were loaded with the highly alkaline waste, slopwater (W-4). In this series two pouches of ELPO and one each of the other membranes were placed in test. Premature seam opening occurred in four of the pouches including an ELPO pouch which, because of its unusual behavior during monitoring, was replaced with a second pouch. The CSPE and the PB pouches remain in test at this writing at more than 2220 days.

Measurements on the pouches taken prior to leaking or dismantling, and those still in test at 2044 days, are presented in Table 8. The results overall show significant weight increases by the pouches and increases in pH and electrical conductivity by the outer liquids. The ELPO pouches showed low permeability early in the exposure but much higher permeability after 300 days. The behavior of these pouches is of particular interest and is described below.

ELPO Pouches

The first of two ELPO pouches was filled with the highly alkaline waste and put into test in February 1977. After 790 days of exposure it failed at the seam and was dismantled and tested. Because of the apparent change in permeability of the pouch wall at approximately 300 days shown in the monitoring (Figure 6), a second pouch was placed in test in January 1979 to verify behavior of the first pouch. The second pouch (P30B) behaved similarly; it showed no significant weight gain until it was under test for about 300 days. The first pouch (P30A) showed a greater rate of weight increase than the second pouch (P30B). Both pouches showed a similar rise in the electrical conductivity of the water outside the pouch, reaching 1,000 μmhos after approximately 300 days. Again, Pouch 30A showed a steeper rate of increase in electrical conductivity after that point.

The second pouch (P30B) was dismantled after 1718 days of test because it had gained so much weight that bursting seemed imminent. The pouch waste was weighed and measured for pH and electrical conductivity as was the outer water. The empty pouch was weighed, measured, and tested for changes in physical properties. Measurements made on the two ELPO pouches, including those made at the time of dismantling, are presented in Table 9.

TABLE 8. POUCHES CONTAINING THE HIGHLY ALKALINE WASTE[a] AT LAST MONITORING BEFORE DISMANTLING OR OBSERVATION OF LEAK

	Pouch					Outer liquid			
Polymer	Liner number[b]	Wall thickness, mil	Effective area[c], cm^2	Pouch number	Elapsed time, d	pH	Electrical conductivity, μmho/cm	Pouch, change in weight, g	Comments
CPE	86	22	486	P32	65	7.9	270	2.7	Leak noted at 93 d; dismantled at 625 d.
CSPE	85	33	329	P31	2044[d]	9.3	1800	36.5	Pouch wrinkled and blistered; odor in water.
ELPO	36	22	486	P30A	753	12.4	10,800	213.6	Leaked at seam at 790 d; blisters noted.
ELPO	36	22	374	P30B	1350	11.1	5460	227.8	Pouch swollen; yellow crystals on outer surface.
PB	98	8	486	P28	2044[d]	9.4	1950	16.8	Pouch has small blisters.
PVC	19	22	425	P29	872	12.5	14,700	152.4	Pouch very stiff; seam failed at 930 d.
PVC	88	20	486	P33	65	9.6	235	...	Leak noted at 93 d; dismantled at 625 d.

[a] "Slopwater," Matrecon waste W-4.

[b] Matrecon liner serial number.

[c] Area of pouch contacting the waste liquid.

[d] Still in test after more than 2,200 days.

TABLE 9. MEASUREMENTS ON THE TWO ELPO[a] POUCHES FILLED WITH SLOPWATER WASTE (W-4)

Parameter	Original waste and ELPO	Exposed pouch P30A	Exposed pouch P30B
Exposure time, days	0	790	1725
Pouch liquid			
pH	13.1	11.9	13.2
Electrical conductivity, μmho/cm	160,000	105,000	84,000
Outer water			
pH	7.0	12.0[b]	8.9[c]
Electrical conductivity, μmho/cm	1.3	90,000[b]	3,100[c]
Filled pouch, original wt., g	N/A	215.13	98.45
Final weight, g	N/A	428.72	346.94
Change in weight, g	N/A	+213.59	+248.49
Empty pouch, original wt., g	N/A	27.62	26.25
Final weight, g	N/A	31.45	28.98
Change in weight, g	N/A	+3.83	+2.73
Original area of pouch, cm^2	N/A	486	374
Final area of pouch, cm^2	N/A	521	383
Change in area, cm^2	N/A	+35	+9
Rates of water transmission into pouch, g/m^2·d			
Initial (0-300 d)	N/A	0.193	0.220
Intermediate (300-1200 d)	N/A	10.387	5.[illegible]29
Final (1200-end)	N/A	N/A	2.[illegible]
Overall curve (0-end)	N/A	3.745	[illegible]
Calculated from increase in pouch liquid			
(0-end)	N/A	5.463	3.812
(300-end)	N/A	7.288	4.530
Analysis of pouch wall			
Volatiles, %	0.15	10.85	8.47
Extractables, %	5.50	2.09	2.85

[a] Matrecon liner number 36; 20 mil thickness.

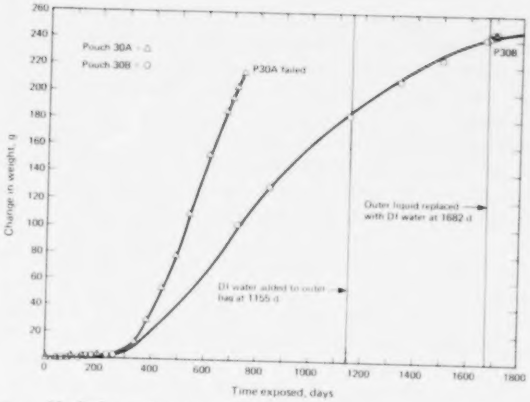
[b] Prior to seam leak the electrical conductivity of the outer liquid was 14,000 μmho/cm and the pH was 12.5.

[c] The outer water had a pH of 10.3 and an electrical conductivity of 8,500 μmho/cm before it was replaced with new DI water on day 1682.

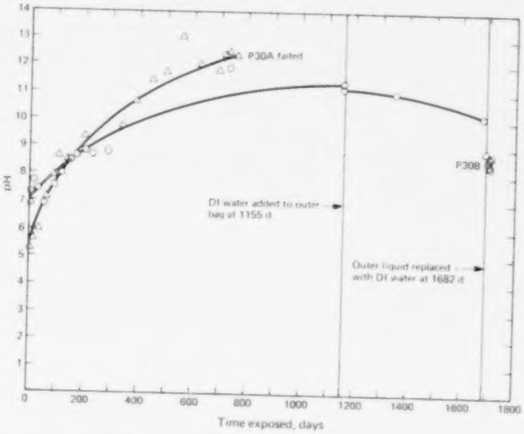
Discussion of Results of Testing the ELPO Pouches

At the time the first pouch (P30A) was dismantled, a seam had opened and a portion of the contents had entered the outer liquid in sufficient quantity to raise the pH to 12 and the electrical conductivity to 90,000 μmho/cm, which approach the original values for the waste (Table 9). Analysis of the pouch wall showed that it had absorbed a considerable amount of water and had a decreased extractables content. The large weight increase of the filled pouch indicated that a high overall transmission of water into the pouch had occurred after the first 300 days of exposure. During the first 300 days, little change in weight had occurred, as illustrated in Figure 6.

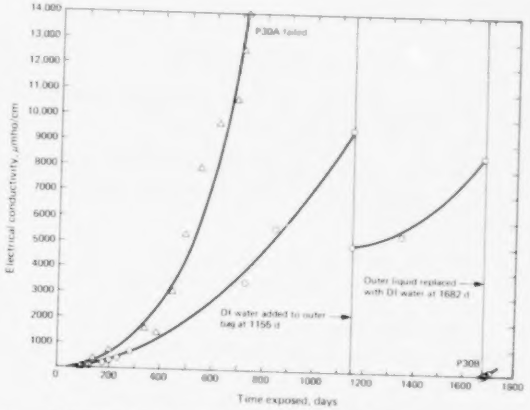
In the case of the second pouch (P30B), the outer liquid had become only moderately alkaline, as shown by the pH and electrical conductivity, indicating that only a relatively small number of ions had penetrated the pouch wall and entered the outer liquid. On the other hand, the



a. Weight change in pouches.



b. pH of outer water.



c. Electrical conductivity of outer water.

Figure 6. Monitoring data for ELPO pouches P30A and P30B containing the highly alkaline waste (W-4).

waste liquid content of the pouch had increased significantly, to the point that it had affected the electrical conductivity of the pouch liquid. The increased water content of the pouch liquid reduced the waste concentration and resulted in a lower rate of water transmission into the pouch because of the lower water concentration gradient across the wall.

Thus, it appears that the highly alkaline waste liquid interacted slowly with the ELPO wall. The effect became apparent during monitoring only after 300 days of exposure when the rates of transmission of the water into the pouch and the electrical conductivity of the outer water increased dramatically. When the pouches were dismantled, measurements of the pouch wall confirmed that some losses had occurred in the tensile strength, elongation, and tear resistance. These data were confirmed by the results of the immersion tests conducted in another study on the same polymer on exposure to this highly alkaline waste liquid (Haxo et al, in press).

The similar results for both pouches indicated the potential reproducibility of the pouch procedure for assessing permeability characteristics of membranes.

Additional Wastes in Pouch Experiments

Four essentially inorganic or dilute wastes were included in our pouch experiments. These were:

1. A mildly acidic waste,
2. A spent caustic waste that is essentially a brine,
3. An industrial waste that contains some minor amounts of organics, and
4. A pesticide waste that has a low concentration of organics.

The pouches in these experiments have been in exposure for more than 1800 days. The monitoring has indicated no unusual behavior by any of the pouches. Preliminary results of these tests are being presented in the final report for Contract 68-03-2173 (Haxo et al, in press).

In addition to the above wastes, a series of wastes containing oily constituents, either in large or small proportions, have been loaded into the pouches and subjected to exposure. Only a few of the pouches have failed, and those remaining are being monitored at exposure times greater than 1650 days. In most cases, the weights of loaded pouches have changed little, but they have changed in hardness and, in several cases, are showing permeation of the oily constituents to the outside. The outside surfaces have become sticky and, in some cases, they fluoresce under UV light. Preliminary results are also being reported in the final report of Contract 68-03-2173 (Haxo et al, in press).

Water-Soluble Tracers

The use of tracers such as inorganic salts and organic dyes has been suggested as a means of detecting leaks in membrane linings of impoundments that contain waste liquids. The question arises whether a membrane liner might allow a tracer to permeate the membrane and thus falsely indicate the presence of a hole. The use of pouches appeared to be a means of determining whether specific tracers could permeate membrane liners.

Three water-soluble tracers were tested in pouches of several lining materials. These tracers included one inorganic salt, lithium chloride, and two water-soluble organic dyes, fluorescein and Sevron Red. Lithium chloride is generally found only in trace amounts in soil and has been used as a tracer in waste impoundments to detect leaks. The organic dyes have also been used for tracing water flow. Information on the organic dyes included in this study appears in Table 10.

The pouches that were fabricated and the liquids loaded into them are listed in Table 11. Two pouches each of HDPE and PB were filled with 1% aqueous sodium fluorescein and Sevron Red solutions. Previously, only one pouch was used for a test, but two were used in this experiment to develop information on the reproducibility of the permeability observations. All the pouches were placed in deionized water each in individual containers.

TABLE 10. DYES USED AS TRACERS IN POUCH EXPERIMENTS

Dye	Color index number	Color	Solubility	Description
Automate Red B	Solvent red 164	Red	Petroleum products	Proprietary AZO dye
Fluorescein-sodium	Acid yellow 73	Yellow-red	Water	$C_{20}H_{10}O_5Na_2$-yellow-green fluorescence in neutral or alkaline solutions
Fluorescent Yellow	Solvent red 175	Brown oil	Xylene, acetone	Organic, proprietary yellow-green fluorescence
Methyl violet	680	Yellow at pH 2-3.1 Violet at pH >3.1	Water, alcohol, chloroform	$C_{25}H_{30}ClN_3$
Sevron Red	...	Red	Water	Cationic proprietary dye

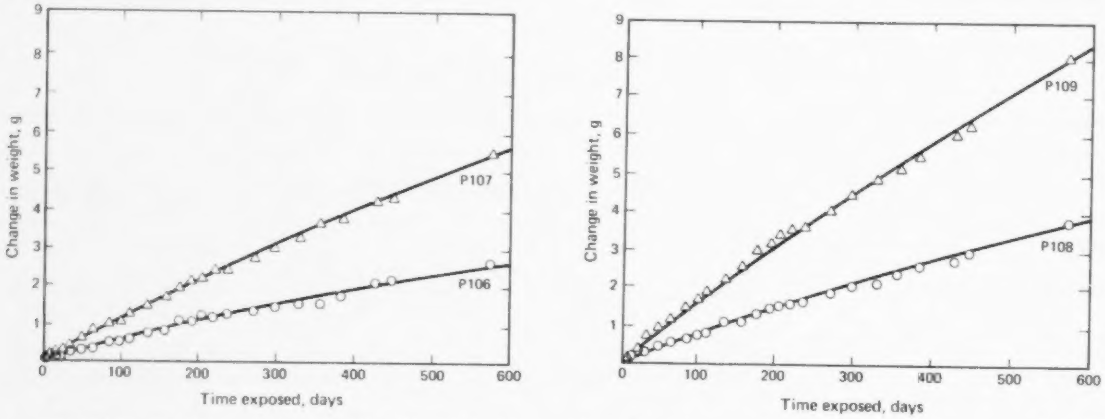
TABLE 11. POUCHES WITH AQUEOUS TEST LIQUIDS CONTAINING WATER-SOLUBLE TRACERS

Liner material			Tracer			
			Lithium chloride		Fluorescein	Sevron Red
Polymer	Number	Thickness, mil	5%	10%	1%	1%
PVC	137	30	106	107	110	...
PVC-OR	146	30	108	109	111	...
HDPE-A	180	20	...	...	112,113	114,115
PB	221	30	...	...	116,117	118,119

Monitoring

The pouch assemblies were monitored regularly by measuring the weight of the pouches, measuring the pH and electrical conductivity of the outer liquids, and by visual observations with normal and UV light for the permeation of the dyes. The weight changes in the PVC pouches containing 5 and 10% solutions of LiCl are shown in Figure 7.

At 573 days of exposure the pouches of polyvinyl chloride with the LiCl solutions increased in weight in differing amounts depending upon the concentration of the LiCl in the pouch and the specific PVC membrane. The pouch with a 10% concentration of LiCl increased in weight at twice the rate of the pouch with the 5% LiCl solution. On the other hand, the electrical conductivity of the outer water exhibited almost no change during this period. This result indicated that the water passed through the pouch walls into



a. Pouches of PVC 137. Pouch 106 contains 5% LiCl, and Pouch 107 contains 10% LiCl.

b. Pouches of PVC-OR 146. Pouch 108 contains 5% LiCL, and Pouch 109 contains 10% LiCl.

Figure 7. Weight changes of PVC pouches containing 5 and 10% aqueous solutions of LiCl during immersion in DI water.

the pouch, but little if any lithium chloride passed through the pouch walls into the outer water.

All 6 pouches with 1% aqueous solution of sodium flourescein showed indications of transmission through the membrane, particularly in the case of the PVC-OR pouch. Under UV light, fluorescent specks showed on the surface of some pouches, in scratches, and at corners where the membrane had been thinned during heat-sealing. Also, observations under UV light indicate that a small amount of the organic dye permeated the PVC-OR wall as there was distinct fluorescence of the outer water. When the pH of the outer water was increased, traces of fluorescence appeared under UV light for all pouches. The gains in weight of the filled pouches were very small.

In the case of the HDPE-A and PB pouches that contained 1% aqueous solution of Sevron Red, also water soluble, no signs of dye appeared in the outer water or on the outside of the pouches in 440 days. The weight gains of the pouches were small, i.e. 0.20 g for HDPE-A pouches and 0.32 g for the PB pouches. Based on the weights of pouches that have been dismantled, it appears that the weight gains were in the pouch walls, presumably by absorption of outer DI water. Overall, the results indicate that Sevron Red probably does not permeate the walls, but, if so, only at a very slow rate.

Organics and the Use of Tracer Dyes

In preliminary experiments using an organic vapor transmission test similar to the moisture transmission E96 test, we observed relatively high transmission rates for some organics through polymeric membrane materials. The pouch procedure appeared to be an appropriate method to assess the permeability of selected materials to the organics and to assess the permeability of organic tracer dyes through the membranes. Consequently, a series of experiments was performed with different membranes and organics.

A series of pouches was prepared of HDPE, HDPE-A, and PB (Table 12). All of these materials were selected because of their low solubility in organics and their low extractables contents. Also, leakproof pouches could be made relatively easily with heat-sealed seams. The two solvents that were selected were xylene and acetone with Fluorescent Yellow and Automate Red in 1% solutions in the solvents (Table 10). Duplicate pouches containing these solvents were placed in glass jars of distilled water and in the respective solvents. In the latter configuration permeation of the dye could be observed.

Monitoring of the pouches was performed principally by measuring their weights as a function of time. The odor of the outer liquids in the jars was also observed as well as the appearance of the

TABLE 12. SERIES OF POUCHES CONTAINING ORGANICS WITH DYES
Matrix of Liner Materials and Test Liquids

Liner material			Liquid in pouch					
Polymer	Number	Thickness, mil	Acetone[a]		50:50 Acetone[b]:water		Xylene[c]	
			In water	In acetone	In water	In acetone	In water	In xylene
HDPE	184	30	132,133	134,135	...	...	136,137	138,139
HDPE-A	180	20	156,157[d] 128,129	158,159[d] 130,131	148,149 ...	150,151 ...	152,153[e] 124,125	154,155[e] 126,127
PB	221	30	140,141	142,143	...	...	144,145	146,147

[a] Acetone + 1% Automate Red.

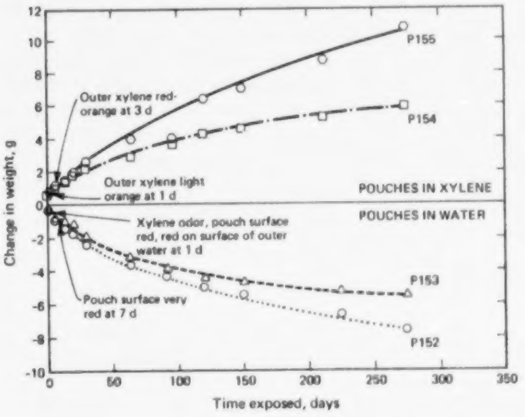
[b] 50:50 acetone:DI water with 1% methyl violet.

[c] Xylene + 1% Fluorescent Yellow.

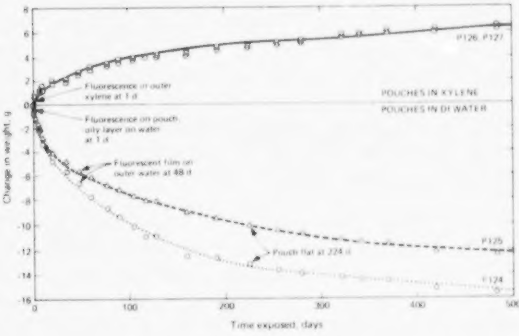
[d] Acetone with 1% Fluorescent Yellow.

[e] Xylene with 1% Automate Red.

dyes either on the surface of the pouches or in the outer liquid. The weight changes are illustrated in Figures 8 and 9.

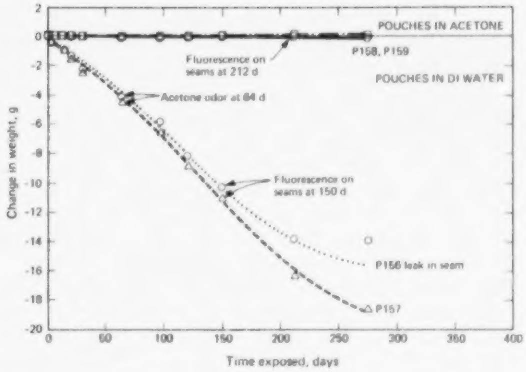


a. Pouches of 20 mil HDPE-A (180) filled with xylene and 1% Automate Red. Pouches 154 (□) and 155 (○) were immersed in xylene. Note lack of movement of xylene into the pouch. Pouches 152 (○) and 153 (△) were immersed in DI water. Note the movement of xylene out of the pouch.

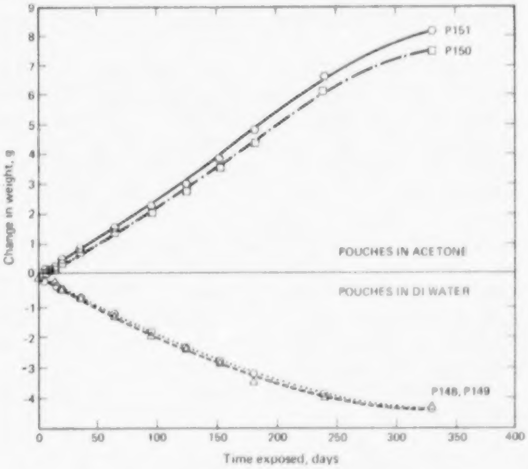


b. Pouches of 20 mil HDPE-A (180) filled with xylene and 1% Fluorescent Yellow. Pouches 126 (□) and 127 (○) were immersed in xylene. Note the movement of xylene into the pouch. Pouches 124 (○) and 125 (△) were immersed in DI water. Note the movement of xylene out of the pouch.

Figure 8. Monitoring the weight change of pouches filled with xylene immersed in xylene or DI water.



a. Pouches of 20 mil HDPE-A (180) filled with acetone and 1% Fluorescent Yellow. Pouches 158 (□) and 159 (○) were immersed in acetone. Note lack of movement of water or acetone. Pouches 156 (○) and 157 (△) were immersed in DI water. Note the movement of acetone out of the pouch.



b. Pouches of 20 mil HDPE-A (180) filled with 50:50 acetone: DI water and 1% methyl violet. Pouches 150 (□) and 151 (○) were immersed in acetone. Note the movement of acetone into the pouch. Pouches 148 (○) and 149 (△) were immersed in DI water. Note the movement of acetone out of the pouch.

Figure 9. Monitoring the weight change of pouches filled with acetone or 50:50 acetone:DI water immersed in acetone or DI water.

The xylene and acetone with the dissolved organic dyes migrated through the HDPE-A pouch walls. The pouches that contained the xylene with the dyes and which were placed in pure xylene increased in weight (Figure 8). The dye in the xylene in the pouch permeated the liner into the outer xylene as indicated by the red color in the outer xylene in the case of the Automate Red and by the fluorescence of the outer xylene in ultraviolet light in the case of the Fluorescent Yellow. Judging from the leveling off of the weight increase and the magnitude, it appears that the weight increase is due to absorption of xylene by the pouch wall.

In the case of a similar pouch placed in water, the xylene migrated out of the pouch into the water but, because it is not soluble in water, the xylene floated to the top of the outer water. The dye permeated the pouch wall and, because it is a solid and insoluble in water, it precipitated on the outside surface of the pouch. The outer water did not fluoresce in UV light.

In the case of the pouches (P156, P157) that contained acetone with Fluorescent Yellow dye and placed in water, the acetone also permeated the pouch wall; but, because acetone is totally miscible with the water, it dissolved in the water to form a dilute solution. The dye also permeated the pouch wall and precipitated on the outer surface causing it to fluoresce under UV light. When acetone was the outer liquid, the dye permeated into the outer acetone but the pouches did not change in weight. This behavior indicates that the pouch wall is not absorbing acetone.

To assess the effects on concentration on transmission rates, another series of 20 mil HDPE-A pouches containing a 50:50 mixture of acetone and water was placed in acetone and in DI water in closed quart jars. Methyl violet, which is soluble in both acetone and water, was added as a tracer to the mixture at 1% concentration. Changes in weight of the pouches up to to 300 days are shown in Figure 9b. The pouches in water lost weight, leveling off as the acetone concentration in the pouch dropped and that in the outer water increased. The pouches placed in the acetone as the outer liquid gained weight as the acetone permeated into the pouch. Again, the rate of transmission dropped as the concentration of acetone in the pouch increased.

The initial rate at which the acetone in the 50:50 mixture moved into the outer water was less than half that of the acetone in the pouch with the 100% acetone (compare Figures 9a and 9b). Calculated rates are, respectively, 1.68 vs 5.68 g/m^2d for the losses of acetone from the pouch. The methyl violet did not appear to have permeated the HDPE-A walls.

DISCUSSION

The primary value of the pouch test is its ability to assess the permeability of liner materials in a condition that simulates some aspects of a lining in a pond. The results indicate the extent of permeation of several waste constituents simultaneously -- water, dissolved ions (both cations and anions), and organics.

Permeability to Water

The pouches with the highly acidic waste (W9) showed the transmission of water from outside to inside the pouches. Deionized water in the outer bag was transmitted into the concentrated waste inside the pouch by osmosis resulting from the large concentration gradient across the wall (Table 7). Even more striking was the behavior of the pouches containing the highly alkaline waste (slopwater), particularly the pouch fabricated of ELPO which gained major amounts of water.

Of the nine pouches filled with the 5% NaCl aqueous solution, eight showed the transmission of DI water from the outer bag into the pouch, as judged by the increased weight of the pouch contents (Table 4). The ninth pouch, CSPE 55 (P76), gained in overall weight but showed a weight loss for the liquid inside the pouch, which indicates absorption of the pouch liquid by the wall and probably little or no transmission through the wall.

The effect of the concentration gradient across the pouch wall is clearly demonstrated in the PVC pouches with LiCl (Table 13). The pouches containing 5% LiCl show a rate of transmission that is approximately half that of the pouches with 10% LiCl. The pouches with solvents

TABLE 13. TRANSMISSION RATES[a] THROUGH WALLS OF POUCHES IMMERSED IN DEIONIZED WATER

Parameter	Polymer				
	HDPE	HDPE-A	PB	PVC	PVC-OR
Liner number	184	180	221	137	146
Thickness, mil	30	20	30	29.0	30.0
Specific gravity	0.951	0.949	0.907	1.283	1.239
Extractables, %	0.73^{b}	2.09^{b}	3.68^{b}	30.14^{c}	34.61^{c}
Area of pouch, cm^2	142	334	115	361	361
Pouch liquid					
Acetone, g/m^2d	-0.866-A (P132,P133)	-6.53^{d}-A (P128,P129)	-1.316-A (P140,P141)	...	...
		-5.68^{e}-A (P156,P157)			
50:50 acetone: water, g/m^2d	...	-1.68^{f}-A (P148,P149)	...	...	...
		$+2.09^{f,g}$-A (P150,P151)	...	...	...
5% LiCl water solution, g/m^2d	...	...	...	+0.143-W (P106)	+0.208-W (P108)
10% LiCl water solution, g/m^2d	...	...	...	+0.286-W (P107)	+0.448-W (P109)
Xylene, g/m^2d	-1.788-X (P136,P137)	-16.84^{e}-X (P124,P125)	-4.40-X (P144,P145)	...	...
		-8.48^{d}-X (P152,P153)			
MVT-E96, g/m^2d	...	...	0.084	1.10	1.94

[a] Transmission rates in g/m^2d from pouch liquid into outer liquid indicated by negative sign, i.e. loss of weight by the pouch. Transmission values were determined graphically from data in the early portion of the pouch weight-time curves. A = acetone; W = water; X = xylene.

[b] With methyl ethyl ketone.

[c] With carbon tetrachloride - methanol.

[d] With Automate Red (1%).

[e] With Fluorescent Yellow (1%).

[f] With methyl violet (1%).

[g] Acetone was outer liquid.

present different problems with respect to the permeability of water. The pouches filled with acetone or xylene in DI water showed a negative transmission rate indicating the movement of acetone or xylene out of the pouches rather than any water movement into the pouches. The pouches with 50:50 acetone:water show outward movement of acetone when immersed in DI water and inward movement of acetone when immersed in acetone.

Such results indicate that a pond lined with a membrane liner placed in a moist, perhaps saturated, environment in which the water is relatively pure would receive water from the environment outside the pond. Such would be true even if the liner contained no holes or breaks. In the diffusion process, each constituent migrates through the liner as an independent molecular species.

Permeability to Ions

In the tests with the highly acidic waste (W9) the hydrogen ions in the pouches appeared to have migrated through the walls; the pH of the outer solution dropped and the electrical conductivity increased apparently due to increased hydrogen ion concentration. Differences in the permeabilities of the different sheetings are quite apparent. Also the rates of transmission of ions varied. In the experiments performed, the sodium, lithium, and chloride ions showed little tendency to permeate polymeric sheeting. Even at high concentration gradients, the electrical conductivity of the outer liquids remained low except where there were small leaks at seams. The low conductivity values may also have resulted from the migration of soluble compounding ingredients out of the pouch walls or residuals from liner manufacture.

Permeability to Organic Liquids

The polymeric membranes, which are organic materials, show permeability to organic molecules, though transmission rates appear to vary greatly and probably depend on the solubility of the permeating organics in the membrane.

Such solvents as acetone and xylene permeated the walls of the pouches when the pouches were placed in DI water. The acetone permeated the walls and dissolved in the outer water; the xylene permeated but, because it is not soluble in water, rose to the surface. When the pouches with the acetone and xylene were placed in the same solvents, the movement was into the pouch where the solvent contained dissolved constituents, either organic dyes or water.

Several of the waste liquids contained oils which permeated the walls of the pouches resulting in a film of oil being formed on the outside of the pouches. Since the oils were not soluble in water, they tended to remain on the surface of the pouch and stop further movement of oils through the wall. If the oils had been soluble in the water, the concentration of the oil on the downstream side of the membrane would have been lower and migration of the oil would have continued. Clearly, some constituents of the organic wastes have permeated the pouch walls and dissolved in the water in the outer bags, but direct analyses of these waters were not made.

Permeability to Organic Dyes

The dyes are also organic chemicals and show varying permeation. Three water-soluble and two organic-soluble dyes were studied in pouch experiments at 1% concentrations. The water-soluble types included sodium fluorescein, Sevron Red, and methyl violet. The sodium fluorescein showed positive transmission through PVC-OR, and trace transmission through HDPE, PB, and PVC. Sevron Red in water showed no detectable transmission through HDPE-A and PB. Methyl violet in the 50:50 acetone:water mixture showed no detectable transmission through HDPE-A. On the other hand, the two organic-soluble dyes, Automate Red and Fluorescent Yellow, in the pouches containing acetone and xylene quickly permeated the HDPE-A pouch walls. These dyes dissolved in the outer liquid of the pouches immersed in xylene or acetone and precipitated on the outside of the pouches immersed in DI water; both dyes are insoluble in water. These results again show the permeability of polymeric membranes to organic molecules.

Comparison of Pouch Results with Other Methods

The relative ordering of the permeabilities among the six polymeric membranes is presented in Table 14 for water and hydrogen ions as measured by pH and electrical conductivity. In the same table the relative permeabilities as measured by moisture vapor transmission in the E-96 test are also presented.

The pouch test results indicate that the ELPO has the lowest permeability to water and to the hydrogen ions and the PB has the second lowest. The highest permeabilities were shown by the CPE and the two PVC's. The pouch of CPE showed a low permeability during the early stages, comparable to the values indicated by the moisture vapor transmission; however, after a year of exposure, during which the changes in weight of the pouch, the electrical conductivity, and pH were small,

TABLE 14. ORDER[a] OF POLYMERIC MEMBRANE PERMEABILITY TO WATER AND HYDROGEN IONS, IN POUCH TEST WITH ACIDIC WASTE, "HNO_3-HF-HOAc" (W-9), AND TO MOISTURE VAPOR IN ASTM E96 TEST

Liner material			Pouch Status at 1887 d			Moisture vapor transmission, E96	
Polymer	Number[e]	Thickness, mil	Water[b]	Electrical conductivity[c], µmhos/cm	pH[d]	g/m² d[f]	Order
Chlorinated polyethylene	86	22	5	6	5	0.643	3
Chlorosulfonated polyethylene	85	33	4	3	2	0.438	2
Elasticized polyolefin	36	22	1	1	1	0.142	1
Polybutylene	98	8	1[g]	2[g]	...	...	...
Polyvinyl chloride	19	22	2	4	4	2.78	4
	88	20	3	5	3	2.94	5

[a] Order of increasing permeation through polymeric membranes in test. 1 = Least permeable and 6 = most permeable.

[b] Based on change in weight of filled pouch for 400 days of exposure and for 1800 days of exposure.

[c] Electrical conductivity of water in outer bags.

[d] pH of water in outer bags.

[e] Matrecon liner number and thickness, in mils, in parentheses.

[f] Test values.

[g] Extrapolated.

significant increases in weight and conductivity took place. These effects would indicate that the permeability of the CPE increased, probably because of high water absorption. Also, pinholes may have developed in the membrane during the exposure period as the inside of the pouch had a pitted appearance. A failure such as occurred with the PB pouch did not occur at the seams of the CPE pouch to cause the very abrupt increase in conductivity.

There was an indication that the relative order of permeability is not the same for all of the constituents of a waste. In addition, maintaining a membrane in a moist condition appears to be necessary to assess the long-term permeability of membranes that may slowly become affected by the waste liquid. This does not occur in the ASTM E96 moisture vapor transmission test, in which one side of a membrane is at 50% humidity, and the other side is maintained at 100% humidity. Nevertheless, even under these conditions, some increases in moisture vapor transmission have been observed in long-term tests.

Expanding the Pouch Test Method to all Polymeric Membranes

The pouch method for assessing the permeability of membranes over long periods of time and of the durability of the materials in contact with wastes appears to be a highly feasible method, though extended exposures may be required. This conclusion is based on the results with the more flexible sheetings of thermoplastic and partially crystalline materials. Expanding this test method to crosslinked polymers and elastomers, to thicker and more rigid sheetings, and to fabric-reinforced materials appears to be desirable. Achieving good seams in the pouches may require the development of special adhesives and possibly new pouch designs that can accommodate the more rigid materials, e.g. 100 mil HDPE. It is desirable, of course, to use the commercial sheetings to fabricate these pouches and not to depend upon molded containers.

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